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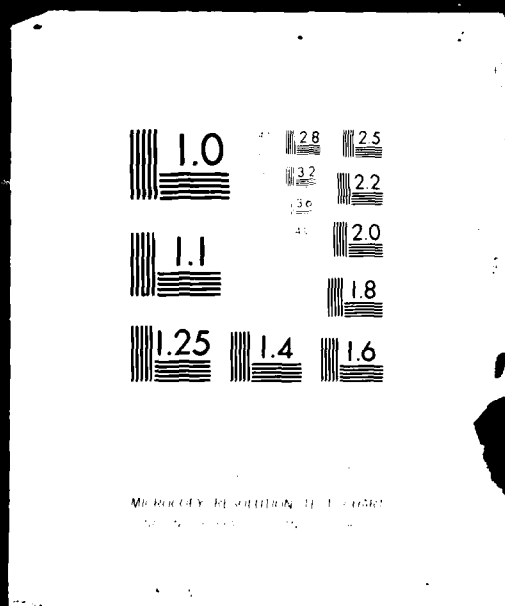
AFAMRL-TR-81-32

LEVEL II

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# FEEDBACK CONTROL FOR FUNCTIONAL ELECTRICAL STIMULATION OF PARALYZED MUSCLE

*CORY D. CARROLL, 2nd Lt, USAF*

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## TECHNICAL REVIEW AND APPROVAL

### AFAMRL-TR-81-32

The experiments reported herein were conducted according to the "Guide for the Care and Use of Laboratory Animals, "Institute of Laboratory Animal Resources, National Research Council.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

*H. E. von Gierke*

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An external harness containing six transducers was developed to provide position information from a cat's rear limbs. The front limbs rest in a sling apparatus while the rear legs are allowed to move in a straight line gait on a motorized treadmill. The aluminum members of the leg harness are nonivasively attached to the skeletal framework of the rear legs. The harness allows a relatively nonrestrictive forward and backward motion while limiting lateral movement of the leg. With the cat in the full harness system, the need for

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posture control during locomotion is eliminated because of the support system of the harness. During locomotion in the harness, electromyographic activity of the essential hindlimb muscles were recorded with the corresponding position information from the harness. These data along with anatomical models of the leg allowed isolation of six "essential" muscles: iliopsoas, semimembranosus, vastus lateralis, biceps femoris, tibialis anterior, and gastrocnemius. Using only these six muscles, locomotion can theoretically be achieved while the cat is in the harness system. From the EMG data, initial activity of the essential muscles during locomotion was obtained and plotted against the cat step cycle.

AFIT/GE/EE/80D-11

FEEDBACK CONTROL FOR FUNCTIONAL

ELECTRICAL STIMULATION OF PARALYSED MUSCLE

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

By

Cory D. Carroll
2/Lt.        USAF

Graduate Electrical Engineering

December 1980

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# FEEDBACK CONTROL FOR FUNCTIONAL
# ELECTRICAL STIMULATION OF PARALYZED MUSCLE

## I.  Introduction

### Background

Disruption of normal neural pathways because of spinal injury results in paralysis below the level of the injury.  Although the central command is no longer present to the alpha motor neuron pool below the level of the injury, if the cell bodies of these neurons have been undamaged the motor units remain healthy and unharmed (Guttman, 1976). However, the muscle fibers will decrease in size because of disuse atrophy.  In about six months to two years the muscle will be atrophied to approximately one-fourth normal size and the muscle fibers will have been replaced mainly by fiberous tissue (Guyton, 1976).  Thus, although healthy motor neurons and muscles are present, the individual remains paralyzed, often for life, due to the absence of central command. Considering that the average patient incurring spinal injury is between 31 and 36 years of age (Smart and Sandurs, 1976) and the increasing longevity of these patients, it has become very important to provide a means of mobility to allow them to move in their environments.

For the paraplegics, the wheelchair has been the most commonly used means of mobility. With the use of specially designed automobiles that can be operated by hand controls, the wheelchair patient is allowed an additional degree of freedom in their environments.  Unfortunately, the life style of these patients is still very restrictive.  In

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addition, psychological problems arise because of the paralysis of their bodies.

Restoring mobility by replacing the lost central command to the alpha motor neurons with direct electrical stimulation of the muscle is a viable alternative to the wheelchair. It is important to realize that direct electrical stimulation can only be used when the cell bodies of the alpha motor neurons remain uneffected by the injury. If these cell bodies are destroyed, the motor neurons die and the muscle suffers irreversible denervation atrophy (Guttman, 1976; Debowitz and Brooke, 1974). By electrically stimulating both agonist and antagonist muscles, the stability required for postural control along with restoration of both hand and leg motion can be achieved (Crochetiere et al., 1967; McNeal et al., 1969; Milner et al., 1970; Kiwerski, 1973; Rehersek and Vodovnik, 1973; Petrofsky, 1978 a, b; Solomonow et al., 1978).

An inovative technique involving stimulation of the motor nerve itself rather than the muscle has been suggested by Petrofsky (1978 a,b, c) and Solomonow (1978). This technique offers the advantage of lower stimulation currents and voltages than those needed with intramuscular electrodes or electrodes placed directly on the skin. However, developing a stimulating system that will, (a) exert a fine control over the tension developed by paralized muscle during isometric contraction, (b) control the velocity of contraction enabling a coordinated movement of limbs, and (c) stimulate the muscles in a manner that will not rapidly fatigue the muscle, is an extremely complicated task that must be achieved before the lame can walk.

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## Purpose

This thesis is concerned with the design and construction of a mechanical harness that will attach to the rear limbs of a cat and act as a feedback device to a computer. The harness will measure the position and velocity of movement of the animal's joints and extremities. Precise positioning of the harness is essential since the computer must have accurate position information in order to compare the actual motion to the desired, predetermined motion of the limb. Restrictive aspects of the harness has been kept to a minimum thus allowing normal forward and backward movement of the leg. Because of the complexity of this project the lateral motion of the leg is limited by the harness.

In addition to construction of the harness, the minimum number of muscles needed for two dimensional movement (i.e., forward and backward) of the leg was determined. This reduction of required muscles simplifies the controlling program required for the stimulation process. Determination of the essential muscles was accomplished by forming anatomical models of the cat's mechanism for walking. The muscles in the leg contributing the essential function of basic locomotion† were isolated and those used for lateral movement and rotational functions were ignored.

Electrodes were then implanted in the "essential" muscles and the signals produced by the central nervous system (CNS) during locomotion

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†The term basic locomotion is defined as the two dimensional supported gait caused when the cat is confined in the harness assembly.

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in the harness were recorded. Six muscles were eventually chosen that
theoretically supply the needed control for basic locomotion. The
sequence of activity of the electromyogram allowed the development of
an initial stimulation pattern of each muscle during the gait cycle.

## Scope

The work presented in this thesis is part of a project conducted by
Jerrold S. Petrofsky, professor of Physiology and Bioengineering at
Wright State University. Formally defined as functional electrical
stimulation of paralyzed muscle, the end goal of this project is to have
a cat walk under its own power after central nervous control to its
rear limbs has been replaced by an external computer controlled stimulus.
The domestic cat was chosen because of the large amount of biochemical,
biomechanical and histological data compiled from previous work. In
addition, the endurance and fatigue characteristics in the muscle of a
cat closely resemble those of man. The concept of external control
concerns the paraplegic community since success would allow use of the
patient's own muscles for basic tasks.

## II. Muscle Anatomy and Physiology

### General Review

Muscles move the limbs and other parts of an animal's body. Each joint of the skeleton in enveloped by a loose capsule and between the two respective bones is the joint cavity. On the sides of each capsule are strong fibrous ligaments that keep the joints from pulling apart. The orientation of the ligaments around the joint defines the motion of the joint. Often the ligaments are only on two sides of the joint which allows the joint to move freely in one direction but restricts motion in another direction. Other joints, particularly those involving the spine, hips and shoulders, not having very restrictive ligaments, can move in almost any direction; that is, they can bend forward, backward, and to either side, or they can even be rotated. In these instances, loose ligaments merely limit the degree of motion to prevent excessive movement in any one direction. For the rear limb of the cat, the knee joint bends in only one direction, the ankle in two, the hip joint in two directions plus an additional rotary motion. Generally, at least two muscles are available for each motion that the ligaments of a joint allows; one for each of the two directions of movement. In the case of movement at the knee joint, for instance, one major muscle is on the front and several muscles are on the back of the joint. There is a similar arrangement of muscles anteriorly (to the front) and posteriorly (to the rear) about the ankle, except that the ligaments of the ankle allow the ankle joint to move from side to side and additional muscles are available to provide the sideway movement.

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All skeletal muscles of the body are made up of numerous muscle fibers ranging between 10 to 80 microns in diameter. In most muscles the fibers extend the entire length of the muscle, and except for about two percent of the fibers, each of those is innervated by only one nerve ending located near the middle of the fiber (Guyton, 1976). The cell membrane of the muscle fiber is called the sarcolemma. At the ends of the muscle fibers the surface layers of the sarcolemma fuse with tendon fibers. The tendon fibers collect into bundles to form muscle tendons which attach to the bones.

Each muscle fiber contains several hundred to several thousand myofibrils, which are illustrated by the small dots in the cross sectional view of Figure 1. Each myofibril in turn has, lying side-by-side, about 1500 myosin fibrils and two times this many actin filaments (Guyton, 1976). These filaments, shown in Figure 2, are large poly-merized protein molecules which are responsible for muscle contraction.

The mechanism of contraction is not completely understood but what is known is that the crossbridges of the myosin filament are attracted to the actin filament and some sort of wrenching action by the cross-bridges causes contraction (Wolaver, 1979). Under resting conditions, the reaction between the actin and myosin filaments is inhibited, but when an action potential travels over the muscle fiber membrane calcium ions are released into the sarcoplasm. (The myofibrils are suspended inside the muscle fiber in a matrix called sarcoplasm, which is composed of the usual intracellular constituents.) These calcium ions allow reaction of the filaments to take place and contraction begins. The
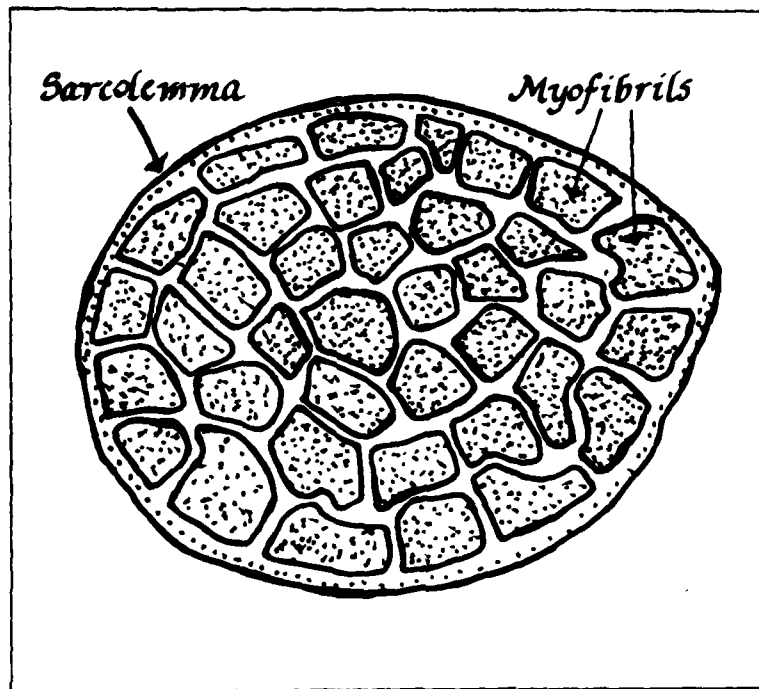
Figure 1. Cross Sectional View of a
Skeletal Muscle Fiber
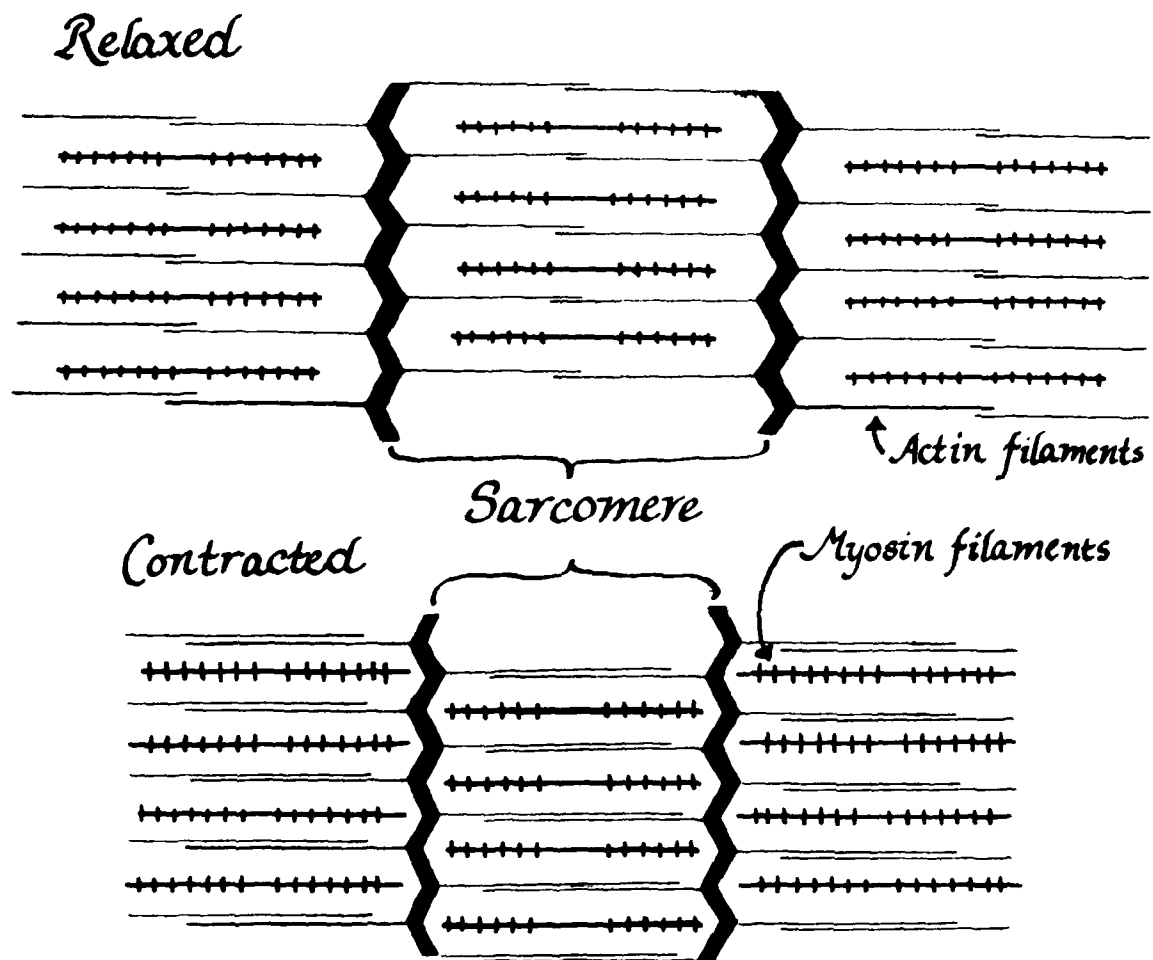
Figure 2.   Relaxed and Contracted States
of a Myofibril

energy needed for the contraction process is derived from the breakdown of adenosine triphosphate (ATP) to adenosine diphosphate (ADP) (Guyton, 1976).

## Innervation

Muscle contraction is controlled by the central nervous system (CNS). Action potentials created by the CNS are transmitted to the specific muscles through the motor portion of the nervous system. Nerve bundles, which carry the signals developed by the CNS, are continually branching, with those branches innervating specified tissue. An illustration of muscle innervation is shown in Figure 3.

The nerve bundle has two means by which it can transmit signals of different strengths. These are (1) to transmit impulses simultaneously over varying numbers of nerve fibers, which is called spatial summation, and (2) to transmit impulses in a slow or fast rate over the same fiber, which is called temporal summation. As an example of spatial summation, if 100 nerve fibers are connected between the spinal cord and a foot muscle, stimulation of one of these fibers will cause only a weak response in the muscle, but simultaneous stimulation of all 100 fibers will cause a strong contraction. Obviously, any number of fibers between 1 and 100 can be stimulated at a time allowing for a fine gradation of contraction force (a process called recruitment).

Temporal summation means changing the strength of a signal by varying the rate of the impulses along the same fiber. If one impulse is transmitted each second, the muscle contracts weakly, but if the impulse rate is varied, the strength of contraction will be proportional

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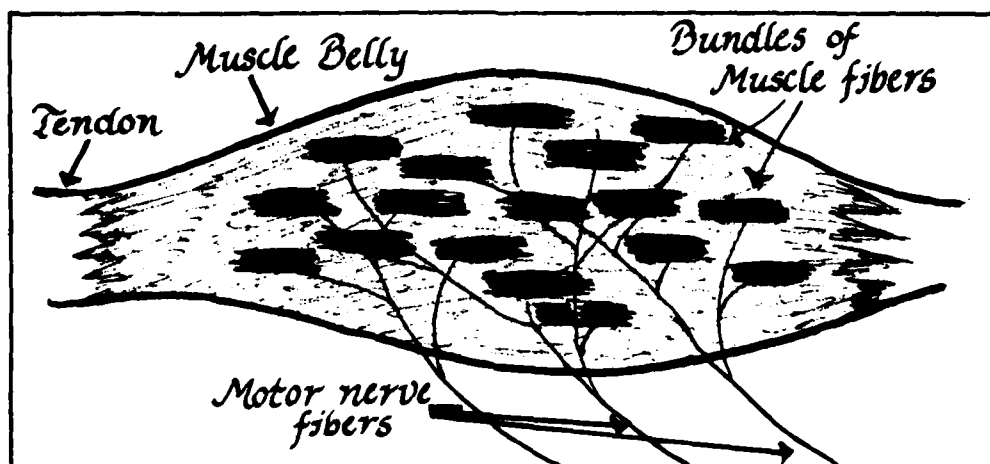
Figure 3. Muscle Innervation
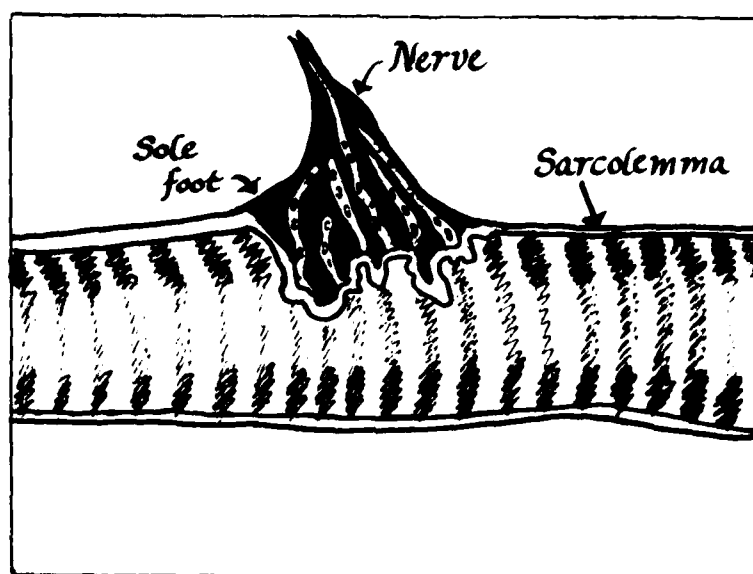


Figure 4. The Neuromuscular Junction

to the rate of stimulation (rate coding). (The upper bound on the impulse rate is determined by the refractory period of the fiber.)

Ordinarily the nerve trunk transmits signals of different strengths by a combination of both the spatial and temporal methods (Guyton, 1974).

Skeletal muscle fibers transmit impulses exactly as nerve fibers do. The normal velocity of transmission in skeletal muscle fibers is about 5 meters per second in contrast to 50 to 100 meters per second in the very large myelinated nerve fibers (Guyton, 1974). Because large myelinated nerve fibers control skeletal muscle, conduction velocity averages 60 meters per second. A signal, therfore, travels from the brain to the muscle extremely rapidly but then decreases in velocity more than 10-fold as it is conducted, across the muscle itself (Guyton, 1974).

The connection between the end of a large nerve fiber and a skeletal muscle fiber is called the neuromuscular junction. As stated previously, each skeletal muscle fiber is usually supplied with at least one neuromuscular junction but rarely more than one. The neuro-muscular junction is illustrated in Figure 4.

Lever Systems

Another factor which determines the force of movement is the manner in which the contracting muscle is attached to the skeletal system. The structure of the joint limits the directions that the corresponding bones can move. The mechanism for which motion of limbs is attained is that of a lever system. A specific example of this would be the extension

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of the cat's rear foot by contraction of the gastrocnemius muscle. Referring to Figure 5, the fulcrum of the lever system is at the ankle and the insertion of the achilles tendon is on the end of the calcaneus bone. Contraction of the gastrocnemius pulls on the calcaneus which rotates the foot toward the ground around the ankle. To support a 5 lb. load at the knee, while in a normal standing stance, the gastrocnemius must produce a 19 lb. contraction force.

Every muscle of the body has its own peculiar shape and length that suit it to its particular function. The muscles of the buttocks are extremely broad but do not contract a long distance. They provide tremendous force for movement at the hip joint, and even a very slight distance of movement at this joint can cause tremendous movement at the foot. At the other extreme, some muscles of the anterior thigh are very long and can shorten a major distance along the thigh, pulling the shank upward at the knee joint and flexing the thigh at the same time.

## Feedback

Kinesthesia is the conscious recognition of the orientation of the different parts of the body with respect to each other as well as the rates of movement of the different parts of the body. These functions are supplied mainly by extensive sensory endings in the joint capsules and ligaments.

Figure 6 illustrates the excitation of seven different nerve fibers leading from separate joint receptors in the capsule of a cat's knee joint. Note that at the 180 degrees of joint rotation one of the

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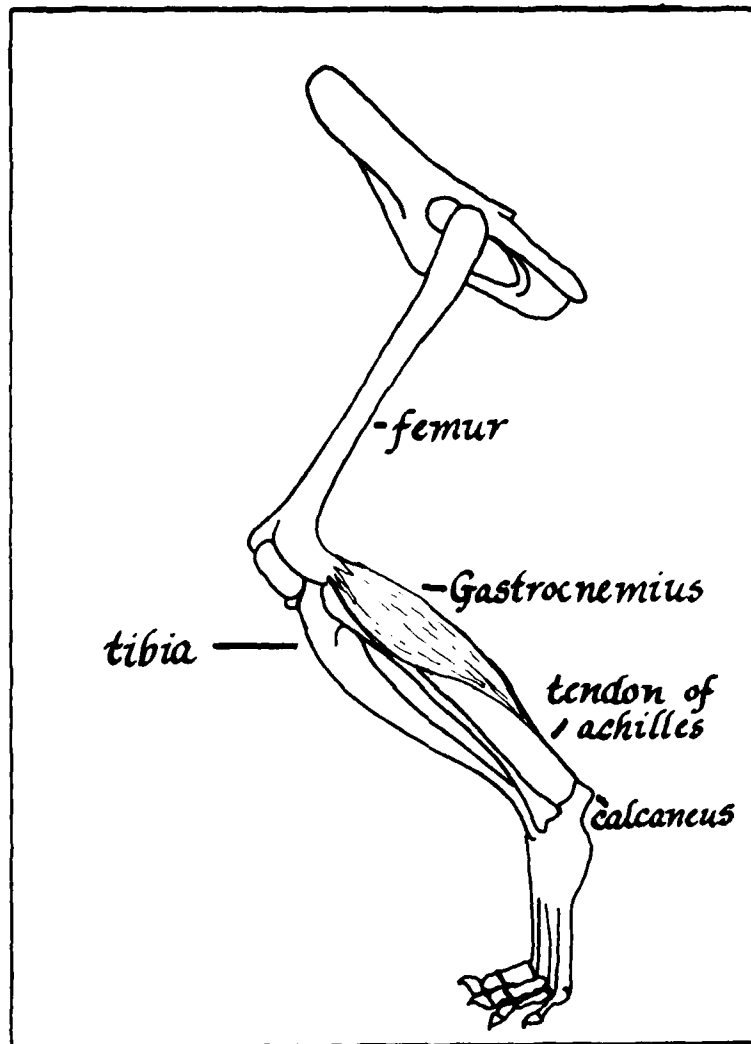
Figure 5. Lever Arm System of the Gastrocnemius
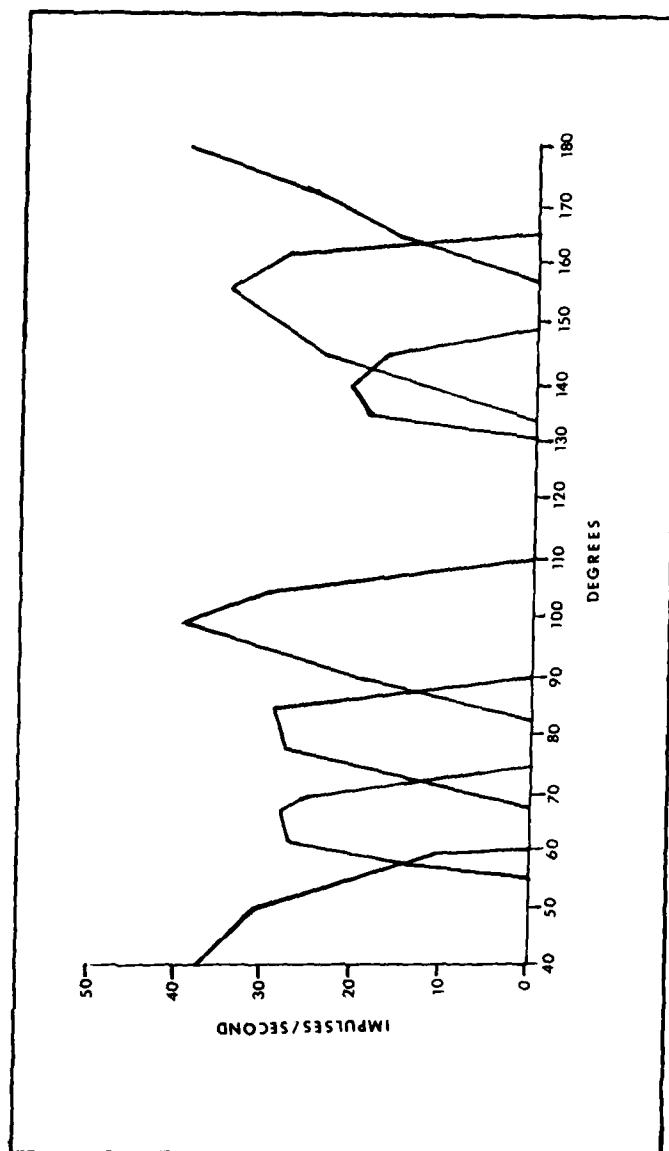
Figure 6. Kinesthetic Signals from the Knee of a Cat at Different Degrees of Rotation (Modified from Skoglund: Acta Physiol. Scand., Suppl. 124,36:1, 1956)

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receptors is stimulated; then at 150 degrees still another is stimulated; at 140 degrees two are stimulated, and so forth. The information from these joint receptors continually feed back the momentary rotation of the joint to the CNS. That is, the rotation determines which receptor is stimulated and how much it is stimulated, and from this the brain knows how far the joint is bent.

Rate of rotation is presumed to be used in this feedback control. Small amounts of specialized nerve endings called pacinian corpuscles are found in the tissue around the joints and have the property of rapid adaptation to the movement of the joints. The mechanism is as follows; the specialized nerve endings produce a strong stimulus when the joint is moved and then fades to a lower steady-state signal within a fraction of a second. This same type of signal is also produced by the position receptors but the difference between initial stimulus and the steady state signal is not as drastic. Nevertheless, this early overshoot in receptor stimulation is directly proportional to the rate of joint movement and is believed to be the signal used by the brain to discern the rate of movement (Guyton, 1976).

Kinesthetic signals are transmitted by the sensory nerve fibers which carry signals very rapidly to the spinal cord and to the brain. This rapid transmission of kinesthetic signals is particularly important when parts of the body are moving rapidly, because it is essential for the nervous system to "know" at each small fraction of a second the exact locations of the different parts of the body; otherwise one would not be capable of controlling further movements.

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### III. Muscles of the Cat's Rear Limbs

This section provides a purely anatomical description of the
muscular structure in the cat's rear limb. The following sections will
contain the description, origin, insertion and action of each muscle
with corresponding figure.† Muscles of the foot along with assorted
small muscles of the limb, whose function does not contribute to the
gross movement of the limb, are not included.

#### Skeletal Structure

The skeletal structure of the cat's left leg is shown in Figure 7
and 8. Figure 7 illustrates the lateral aspect (side view) while
Figure 8 shows the medial aspect (opposite to side view). These figures
will be helpful for visualizing origin and insertion points of the
various muscles presented in the following figures.

---

†Construction of the anatomical illustrations used material presented
by Greenblatt (1954), Crouch (1969) and Donnersberger et al., (1975).

Figure 8. Skeletal Structure of the Cat's
Left Leg : Medial View

Figure 7. Skeletal Structure of the Cat's
Left Leg : Lateral View

## Superficial Muscles of the Thigh

### Medial Aspect (See Figure 9)

1. Sartorius - large band of muscle extending from the crest

    and ventral border of the ilium to the patella.

    Origin     - crest and ventral border of ilium.

    Insertion - proximal end of tibia and patella.

    Action     - adducts and rotates the femur and extends the

    shank.

2. Gracilis - a wide, flat muscle covering most of the thigh

    below the sartorius.

    Origin     - ischial bone and pubic symphysis.

    Insertion - tibia and fascia of shank.

    Action     - adducts the leg.

3. Iliopsoas - a triangular shaped muscle which is caudal to

    the sartorius.

    Origin     - anterior iliac crest.

    Insertion - lesser trochanter of femur.

    Action     - adducts the femur.

### Lateral Aspect (See Figure 10)

4. Gluteus medius - a relatively large muscle in the cat and

    somewhat triangular.

    Origin         - crest and lateral surface of ilium.

    Insertion     - greater trochanter of femur.

    Action         - aids in abducting the thigh.

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5. Gluteus maximus - triangular mass immediately posterior
to the medius.

Origin - last sacral and first caudal vertebrae.

Insertion - fascia lata and greater throchanter of
femur.

Action - abducts thigh.

6. Caudofemoralis - band of muscle posterior to gluteus
maximus and anterior and dorsal to biceps
femoris.

Origin - second and third caudal vertebrae.

Insertion - patella.

Action - abducts thigh and extends shank.

7. Biceps femoris - very broad muscle posterior to the
fascia lata.

Origin - tuberosity of ishium.

Insertion - patella, tibia, and shank fascia.

Action - abducts thigh and flexes shank.

8. Tensor fasciae latae - triangular mass of muscle anterior
to the biceps femoris.

Origin - ilium and fascia.

Insertion - fascia lata.

Action - tightens fascia la...

Figure 10. Superficial Muscles of the
Thigh : Lateral Aspect



Figure 9. Superficial Muscles of the
Thigh : Medial Aspect

Deep Muscles of the Thigh

Lateral Aspect (See Figure 11)

1. Vastus Lateralis — this large muscle lies under the
   fascia lata and covers the
   anterolateral surface of the thigh.

   Origin        — greater trochanter and shaft of femur.

   Insertion     — patella.

   Action        — extends shank.

2. Semitendinosus — a large band of muscle covering the
   posteromedial border of the popliteal
   fossa.

   Origin        — ischial tubrosity.

   Insertion     — medial side of tibia.

   Action        — flexes the shank.

Medial Aspect (See Figure 12)

3. Rectus femoris — narrow band of muscle on the front of
   thigh medial to the vastus lateralis.
   It lies beneath the sartorius.

   Origin        — ilium, anterior to acetabulum.

   Insertion     — patella and patellar ligament.

   Action        — extends shank.

4. Vastus medialis — large muscle on medial surface of thigh,
   posterior to the rectus femoris. It is
   covered by the sartorius.

   Origin        — shaft of femur.

|  |  |  |
|---|---|---|
| | Insertion | - patella. |
| | Action | - extends shank. |
| 5. | Adductor femoris | - large triangular mass of muscle |
| | Origin | - ischial and pubic symphysis. |
| | Insertion | - shaft of the femur. |
| | Action | - adducts and extends thigh. |
| 6. | Semimembranosus | - a large muscle posterior to the adductor femoris. |
| | Origin | - posterior edge of ischium. |
| | Insertion | - medial epicondyle of femur. |
| | Action | - extends thigh. |

Figure 12. Deep Muscles of the Thigh :
Medial Aspect



Figure 11. Deep Muscles of the Thigh :
Lateral Aspect

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## Muscles of the Shank

### Lateral Surface (See Figure 13)

1. Gastrocnemius — a large muscle mass on the dorsal surface of the foreleg.

   Origin — lateral and medial condyles of femur.

   Insertion — tendon of Achilles on calcaneus bone.

   Action — extends foot.

2. Soleus — small band of muscle lying next to the lateral head of the gastrocnemius.

   Origin — lateral surface of the head of the fibula.

   Insertion — calcaneus by tendon of Achilles.

   Action — extends foot.

3. Peroneus — elongated band of muscle occupying the fibular aspect of the shank.

   Origin — lateral aspect of the head of the fibula.

   Insertion — bases of the metatarsals and phalanges.

   Action — extends foot and assists with plantar flexion. Prime mover for eversion of foot.

4. Tibialis anterior — a slender muscle situated on the anterolateral aspect of the tibia.

   Origin — proximal lateral surface of the tibia and corresponding portion of the interosseous membrane which joins the tibia and fibula.

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Insertion             – base of first metatarsal.

Action               – dorsiflexion and inversion of foot.

5. Extensor digitorum – slender, tapered muscle, which must
    longus

                        be separated from the tibialis

                        anterior, which overlaps it.

Origin               – lateral epicondyle of femur.

Insertion             – phalanges.

Action               – extends phalanges.

Medial Surface (See Figure 14)

6. Flexor digitorum – the first head (6a) is covered
    longus

                        partly by the soleus and lies

                        against the central surface of the

                        tibia and fibula. The second head

                        (6b) lies between the long head and

                        medial aspect of the gastrocnemius.

Origin               – first head – tibia.

                        second head – fibula and fascia.

Insertion             – in common by a tendon to the digits.

Action               – flexes foot.

7. Plantaris           – the two heads of the gastrocnemius

                        muscle meet behind an indistinct

                        line. If the two heads are separated,

                        a strong round muscle will be revealed

                        enclosed by the two heads. This

                        muscle is the plantaris.

Origin        - patella.

Insertion     - calcaneus and phalanges.

Action        - flexes phalanges.

Figure 14. Muscles of the Shank : Medial Surface



Figure 13. Muscles of the Shank : Lateral Surface

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IV.  Definition of the Cat Step Cycle

A common method of examining the cat step cycle divides the cycle into two phases, the swing and stance phase. Each of these phases is further divided into two more phases which is illustrated in Figure 15. The flexion (F) phase begins as the foot is thrust off the ground at which time there is a beginning flexion at hip, knee and ankle joints. This phase ends as the extension begins in the knee and ankle. These movements of limb flexion and early extension ($E^1$) comprises the swing (foot off the ground) phase of the step cycle. The stance (foot on the ground) phase involves progressive extension of the hip at increasing speed. During the second phase ($E^2$) the knee, ankle and metatarso-phalangeal (hindpaw structure) joints yield under the animal. This yield is slight in walking but become quite pronounced as the animal converts to high speed locomotion. The notation of the arrows to separate the swing from the stance phase and the dots used to separate F from $E^1$ and $E^2$ from $E^3$ (See Figure 15) will be used in subsequent figures.
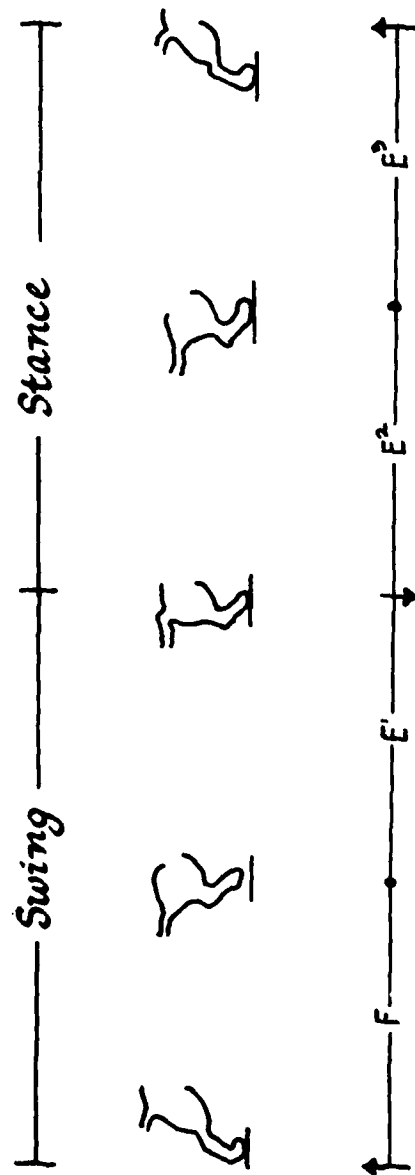
Figure 15. Phases of the Cat Step Cycle

## V.  Reduction of Muslce Groups

Controlling the motion of the cat's leg is extremely complicated.
This can be visualized by the intricate network of the controlling
muscles illustrated in Chapter III.  Stimulation of the muscles normally
used during locomotion by an external computer would require an enormous
software routine.  In addition, the task of surgically implanting the
corresponding muscle stimulators developed by Petrofsky is not feasible
at this time.  These two problems will eventually be solved, but for
initial attempts to control locomotion, a functional gait cycle can be
achieved by concentrating on "essential" muscles.

The criteria for finding the essential muscles is well defined
because of the use of the harness system.† Although the cat has a nor-
mal gait in the harness, the lateral motion, along with rotational
characteristics of the leg, has been virtually eliminated.  These two
restrictions of the leg motion allow for reduction of the number of
needed muscles for locomotion.  A further aspect of the harness imple-
mentation that permits this reduction is that of body support.  With
the sling and tail clamp in use, the cat's haunches are supported, and
therefore, the problem of posture control during locomotion is greatly
simplified.

With the above criteria, a purely anatomical representation of the
muscle structure in the leg was analyzed.  From this analysis, a "first

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†The harness system is described in Chapter VI.

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TABLE I

Nonessential Muscles

| Muscle | Reason Eliminated |
|---|---|
| **Thigh:** | |
| Sartorius | produces rotational motion |
| Gracilis | produces lateral motion |
| Gluteus medius | produces lateral motion |
| Gluteus maximus | produces lateral motion |
| Caudofemoralis | produces lateral motion |
| Tesor Faschae Latea | small contribution to gross movement |
| Vastus Medialis | secondary to vastus lateralis |
| Adductor femoris | produces lateral motion |
| **Shank:** | |
| Soleus | secondary to gastrocnemius |
| Peronus | produces lateral motion |
| Extensor digitorum longus | small contribution to gross movement |
| Flexor digitorum longus | secondary to tibialis anterior |

_cut" in the isolation of nonessential muscles was achieved. Table I lists the muscles eliminated and the reason.

A very good representation showing the location of the remaining muscles is shown in Figure 16 (Goslow, et al., 1973). The straight line length of the muscles depict the distance from the most proximal point of muscle origin to the most distal point of insertion. The presented muscle lengths include the length of tendon of origin and/or insertion. Table II explains the abbreviations used in Figure 16.

From the model shown in Figure 16, six muscles were isolated that theoretically produce the needed forces for locomotion in the harness. In all cases, the characteristic of pure flexion and extension were prime criteria in selection. Accessability of the muscles was included in the selection criteria. This included the ability to isolate the inner-vation and surgically implant the stimulating lead. The essential muscles finally selected are listed below:

     Thigh flexor    -- iliopsoas

     Thigh extensor  -- semimembranosus

     Shank flexor    -- biceps femoris

     Shank extensor  -- vastus lateralis

     Foot flexor     -- tibialis anterior

     Foot extensor   -- gastrocnemius

Figure 17 shows the reduced model (refer to Chapter III for anatomical information of the muscles).
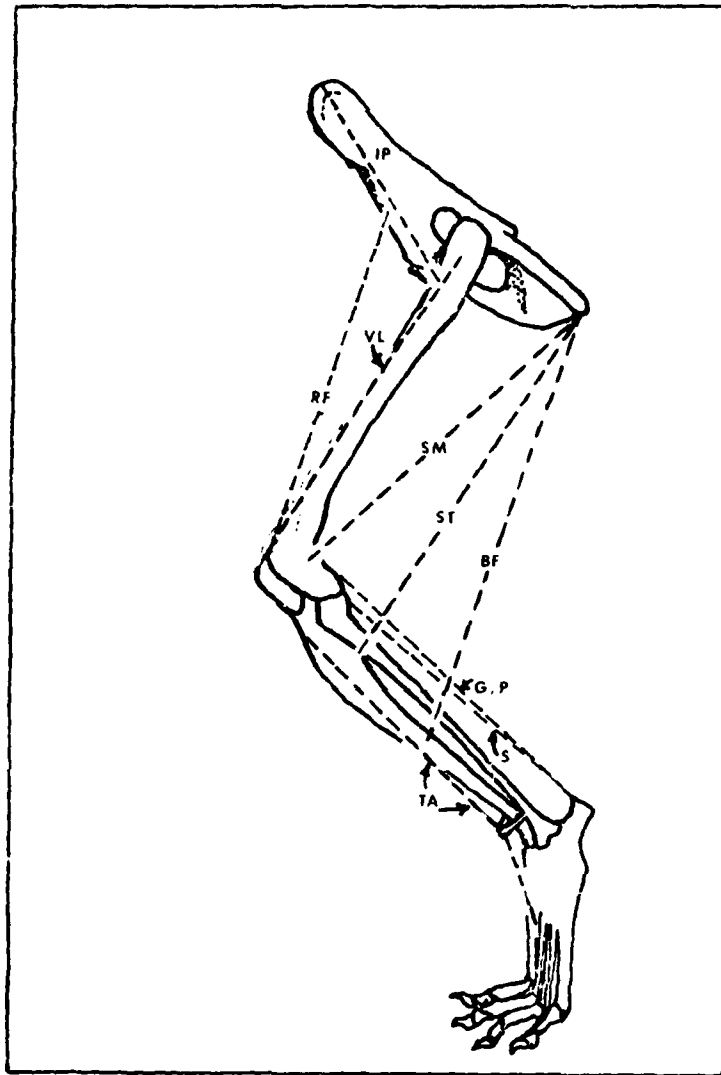
Figure 16. Model of the Major Muscles in the Leg

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## TABLE II

### Anatomical Model Notation

| Abbreviation | Muscle | Refer to Chapter III Figure # |
|:---:|:---|:---:|
| SM | Semimembranosus | 12 |
| RF | Rectus femoris | 12 |
| BF | Biceps femoris | 10 |
| ST | Semitendinosus | 11 |
| G | Gastrocnemius | 13 |
| PL | Plantaris | 14 |
| VL | Vastus lateralis | 11 |
| IP | Iliopsoas | 9 |
| S | Soleus | 13 |
| TA | Tibialis anterior | 13 |
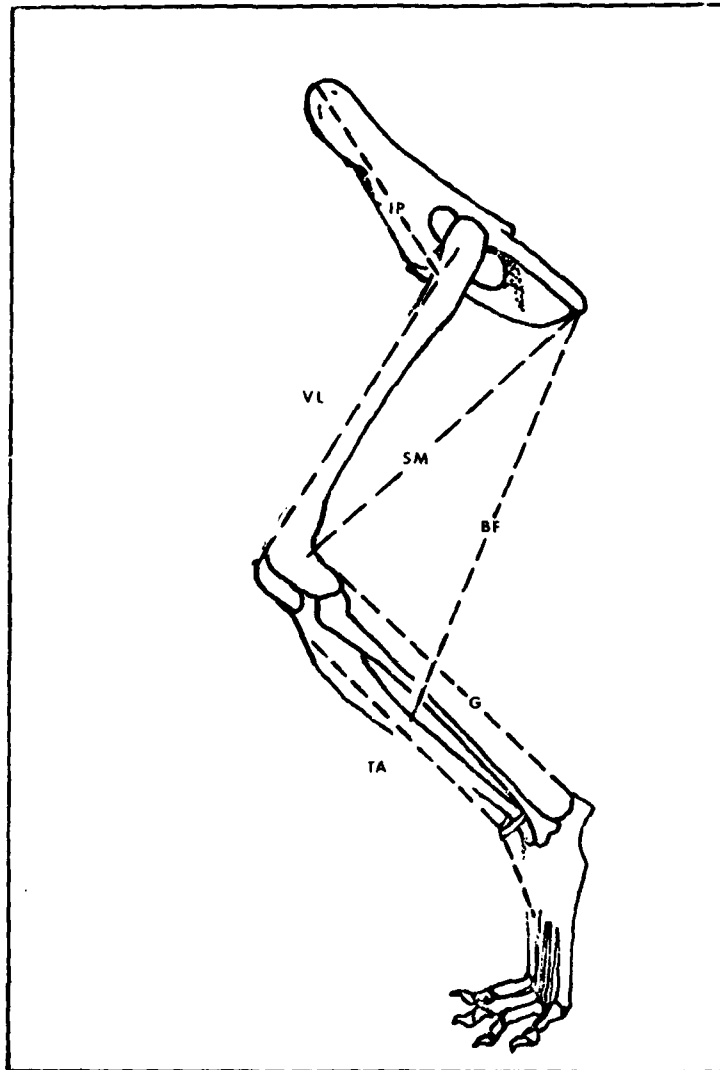
Figure 17.   Reduced Model : Essential Muscles
in the Leg

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Verification of the action of the six muscles chosen was done by analysis of EMG data recorded with position signals from the harness.[†] This data shown in Figure 18 exhibit the expected activity of the essential muscles. In both charts, the first three channels of the graph depict the harness signal. (The noise shown on the left hip signal in Figure 18a is due to a discontinuity in that potentiometer.)

The EMG waveforms shown in Figure 18 are the signals developed directly from the muscles. The absence of the usually characteristic spikes in EMG signals is because of the choice of recording parameters used in the collection of this data. These recording parameters and their influence on the EMG signals is discussed in Appendix B.

Referring to Figure 18a, the gastrocnemius shows initial activity in the $E^1$ phase which corresponds to the preparation of foot placement. The tibialis anterior begins its activity during the $E^3$ phase and peaks at the lifting of the foot. This stimulation causes flexion of the foot during the swing phase.

Extension of the shank caused by the vastus laterais is accomplished during the swing phase, shown by the activity occurring during the F and $E^1$ phase. Flexion of the shank by the biceps femoris, shown in Figure 18b, occurs at the end of the $E^3$ phase and continues throughout the swing phase.

Semimembranosus activity is developed in the $E^1$ phase and continue up to the end of the $E^3$ phase. The contraction of the semimembranosus

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[†]The experimental procedure used to obtain the EMG data is discussed in Chapter VII.
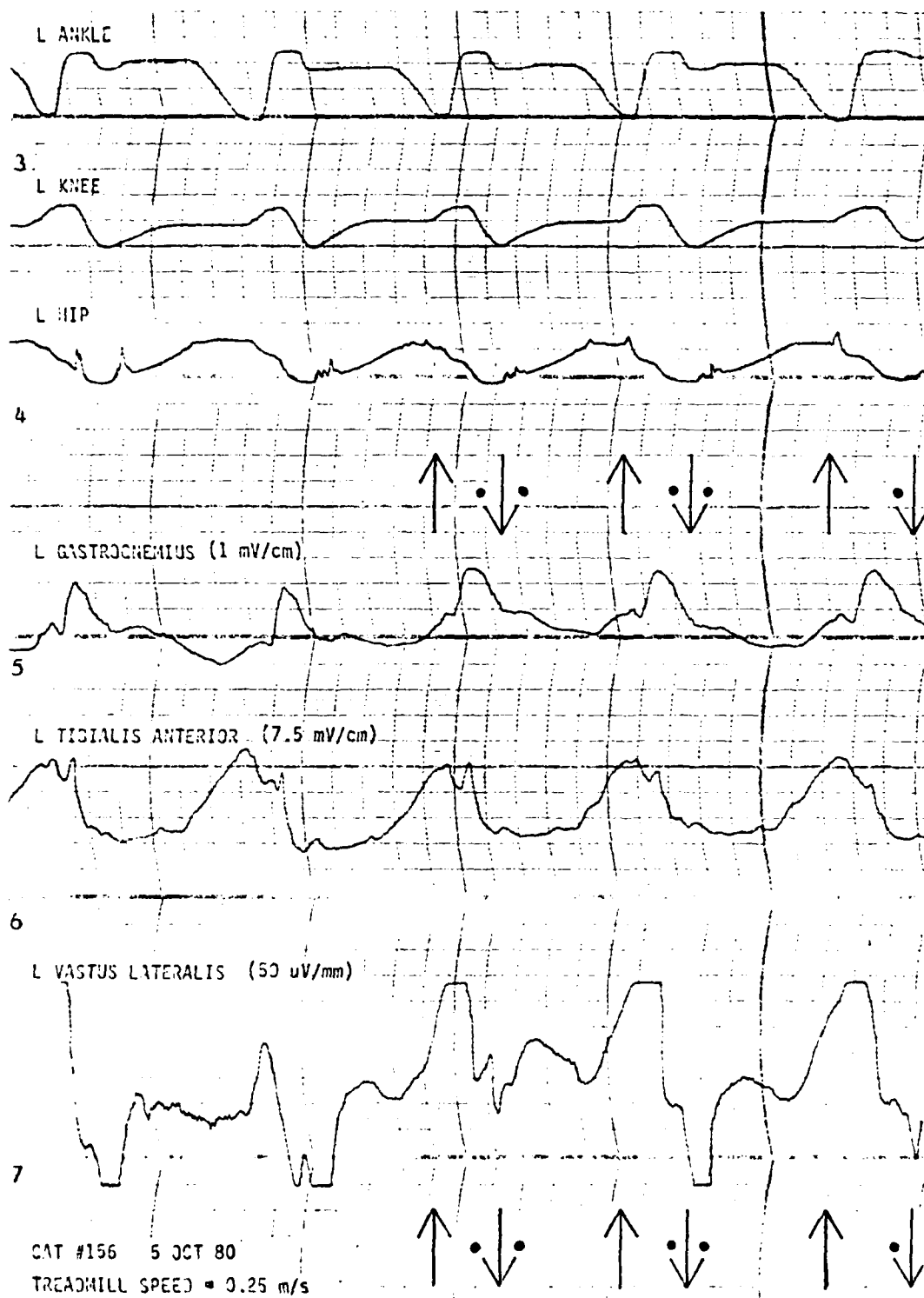
Figure 18. EMG Signals of Essential Muscles and Position Information

L ANKLE

3

L KNEE

L HIP

4

L SEMIMEMBRANOSUS (75 uV/mm)

6

L BICEPS FEMORIS (75uV/mm)

7

CAT #156   7 OCT 30
TREADMILL SPEED = 0.25 m/s

Figure 18b

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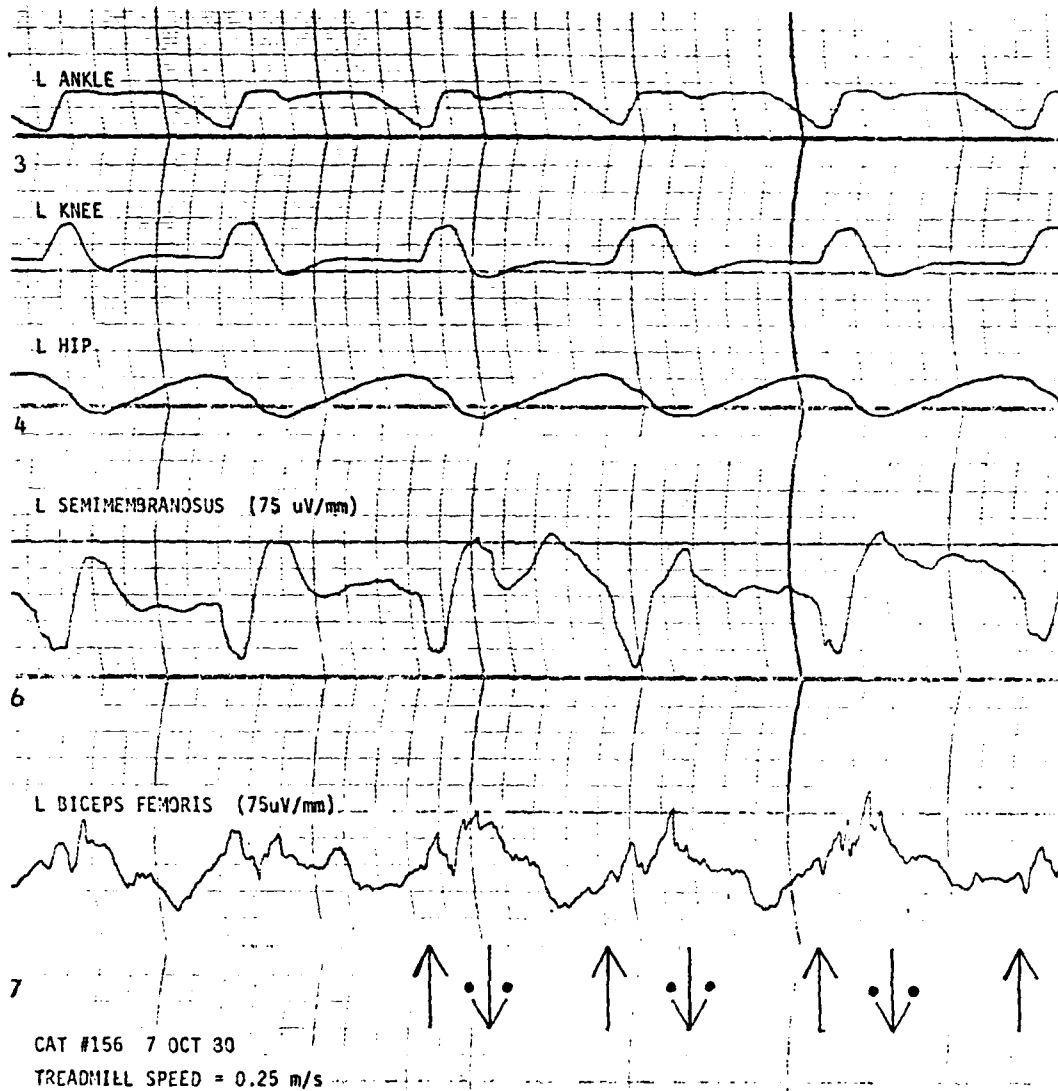
extends the thigh while the foot is on the ground. Iliopsoas EMG
signals are not included because of problems of electrode placement.
However, Engberg and Lundberg (1968) recorded the EMG from the iliopsoas
during a comparable walking speed. The iliopsoas signal displayed
activity throughout the F and $E^1$ phase and develops thigh flexion
during the swing phase.

Additional data were recorded for different treadmill speeds and
is included in Appendix B.

## VI.  Harness

Position feedback information of the cat's rear limbs during
locomotion is developed by an external harness.  The design criteria
for the harness is listed below:

1) Support the animal's front torso.

2) Provide lightweight leg members that will noninvasively attach
   to the rear limbs.

3) Restrict lateral movement of the rear leg and yet allow
   unrestrained forward and backward motion.

4) Allow for variation of physical size for different experimental
   animals.

5) Incorporate measuring transducers to provide position infor-
   mation while keeping the leg member system as lightweight and
   nonrestrictive as possible.

The physical system that fulfills the above constraints is shown
in Figure 19.  The harness assembly is bolted to the treadmill frame and
allows free travel of the treadmill belt.

The treadmill belt is driven by a 1/8 hp variable speed motor.  The
speed of the belt is measured by a simple magnet switching device which
counts the rotation of the driving cylinder.  The motor produced a con-
stant treadmill belt speed once set which ranged from zero to one meter
per second.  The roller system which the belt traveled over was modified
by placing a section of plexyglas over the rollers.  This modification
eliminated the unevenness produced by the rollers and provided a hard
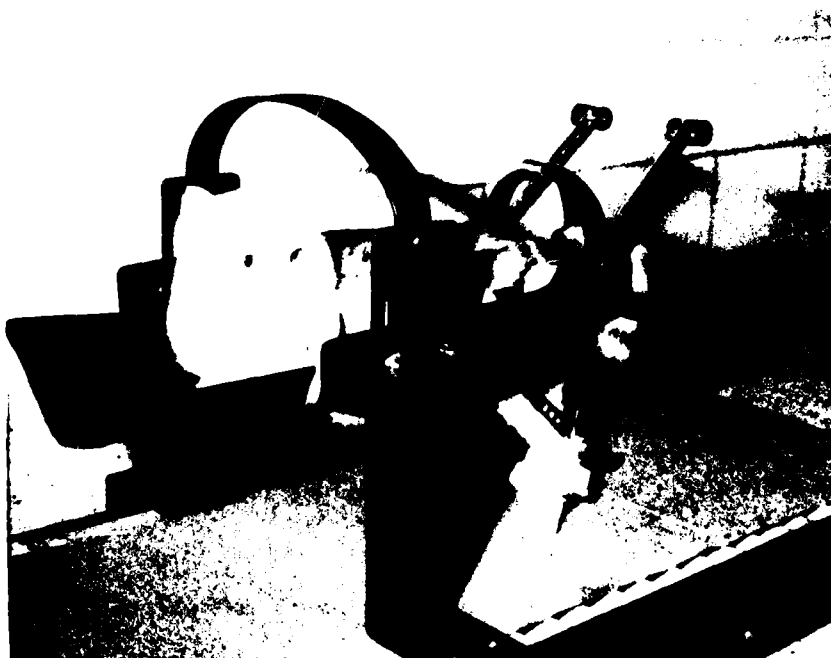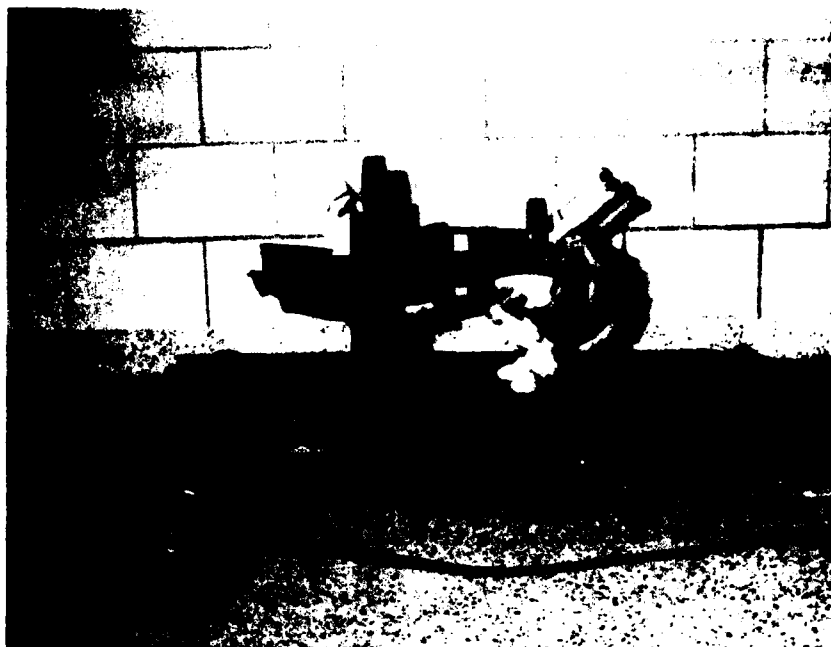flat surface for the cat to walk on.

Figure 19.   Harness Assembly

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## Mechanical Design

The support mechanism is incorporated to keep the pelvic area in a set location while the cat walks on the treadmill. This mechanism used a sling apparatus in which the cat's front paws and torso rests. Slits were initially cut into the sling to allow use of the front paws during locomotion. This modification produced an unfavorable result in that the cat would either drag all four limbs or use the front paws to stop the treadmill belt. With the front paws elevated, there is no significant difference in the gait of the rear limbs.

Aluminum rods provide the side support for the nylon material of the sling. These solid 1/4 in. diameter rods can be bent to conform the sling to the animal's shape. The sling mounting brackets allowed both vertical and horizontal adjustment along with the ability to tilt the sling apparatus. Tie-down straps are available to confine the cat on the sling. These straps were used only during the recovery period of the animal from the ketamine injection. Once walking, the cat seemed quite content to remain in the sling.

Positioning of the leg members is accomplished by the harness positioning arms. Shown in Figure 20, the positioning arms attached to the support frame and determined the vertical height of the cat's hindquarters above the treadmill. Dimensions of the support assembly are shown in Figures 20 and 21.

Actual measurement of the leg position is done by the leg members. Information concerning the design of the leg members was obtained through videotape recordings of unencumbered cats walking on the treadmill.
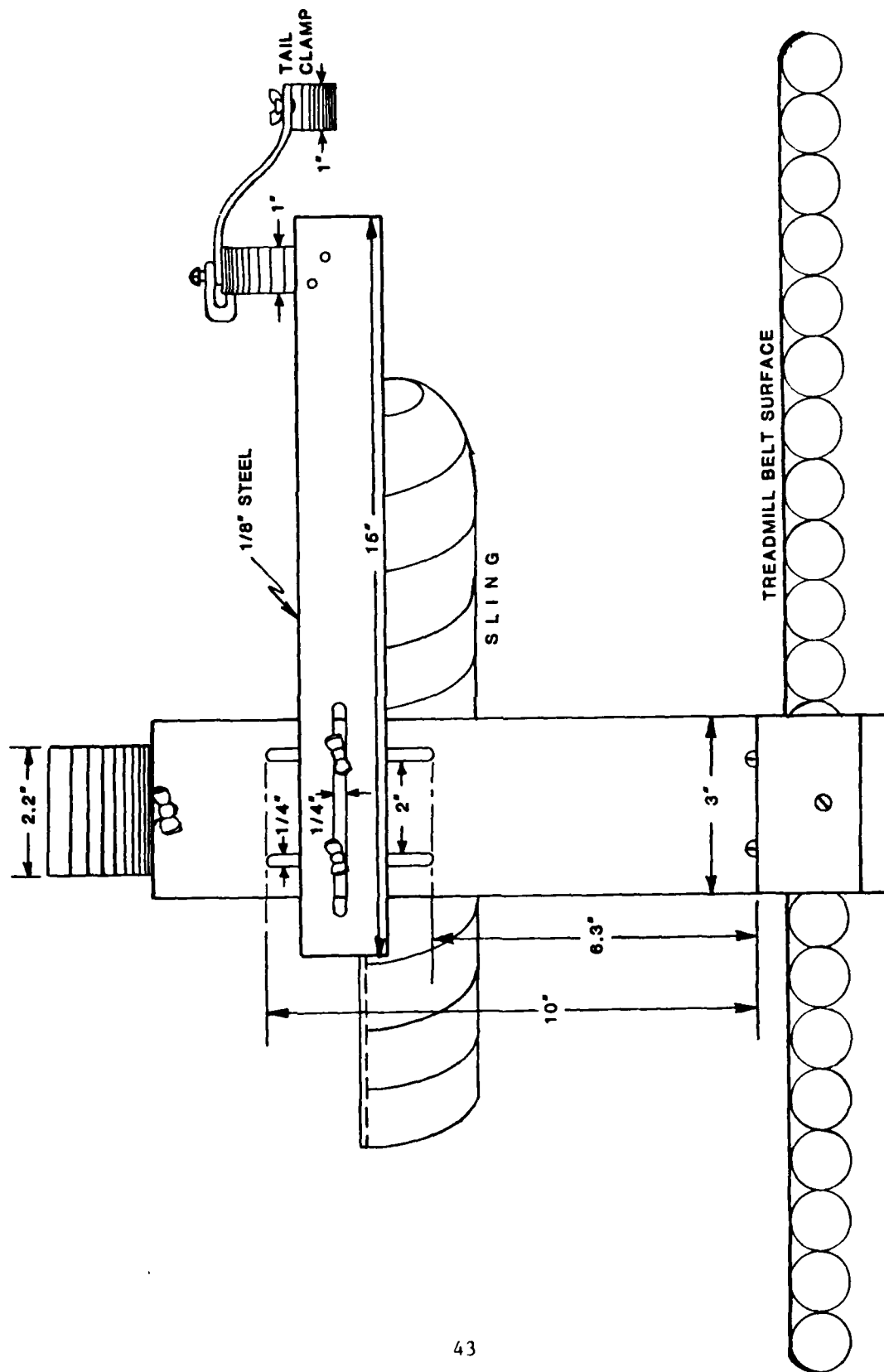
42

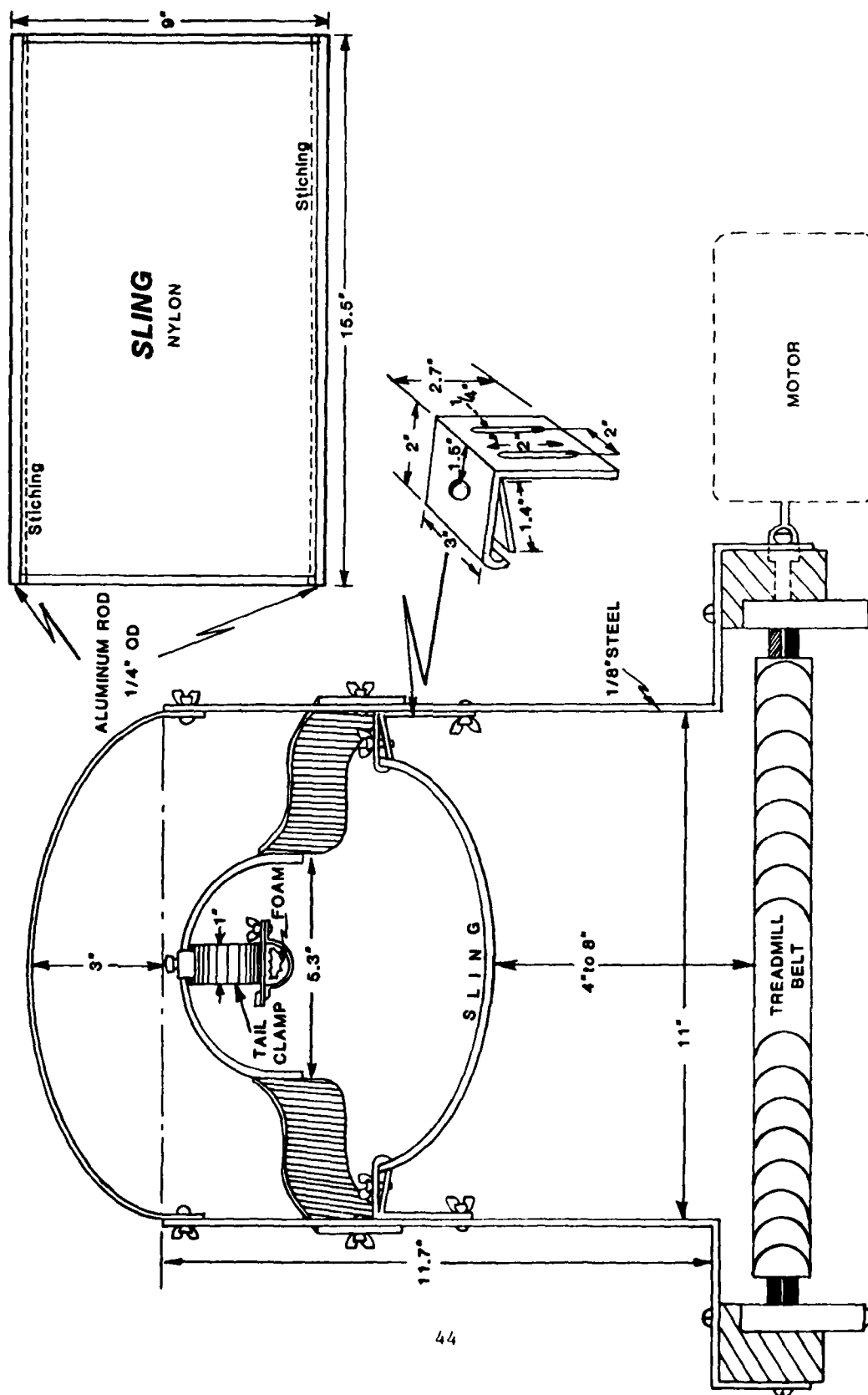Figure 20. Harness Support System : Side View

Figure 21. Harness Support System : Front View

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A transparent enclosure shown in Figure 22 was placed over the treadmill
to keep the animal on the treadmill belt. A grid system painted on one
side of the enclosure provided a coordinate system for motion analysis.
The result was used to specify the range of motion of the leg members.
The film also provided a means for visual comparison of the gait cycle
during unrestrained locomotion and during locomotion in the harness.
Figure 23 illustrates the final design of the leg members.

The leg members correspond to the skeletal bones of a cat's leg.
They are defined as 1) the femur member, 2) the tibia member, and
3) the metatarsal member. Rotation of the leg members is at the same
points of rotation of the limb, i.e., the hip, knee and ankle. Teflon
washers used at the knee and ankle pivots reduced the friction and
allowed free movement of the leg members.

The location of the hip pivot of the femur member is at the
junction of the cat's femur into the ischium. Since the harness does
not allow spinal arching, the cat's haunches need to be supported so
that the hip pivot of the harness and the cat's hip joint will maintain
the geometry desired in its preparation. To accomplish this support,
a tail clamp was designed (See Figures 20 and 31). The tail clamp along
with the sling assembly provides the needed support for hip positioning.

Attachement of the leg members to the cat's leg is done at the
metatarsal member. A styrofoam pad which is contoured to the cat's foot
provides the contact point. Velcro fasteners are used to strap the
styrofoam piece to the foot. When attached, the leg members faithfully
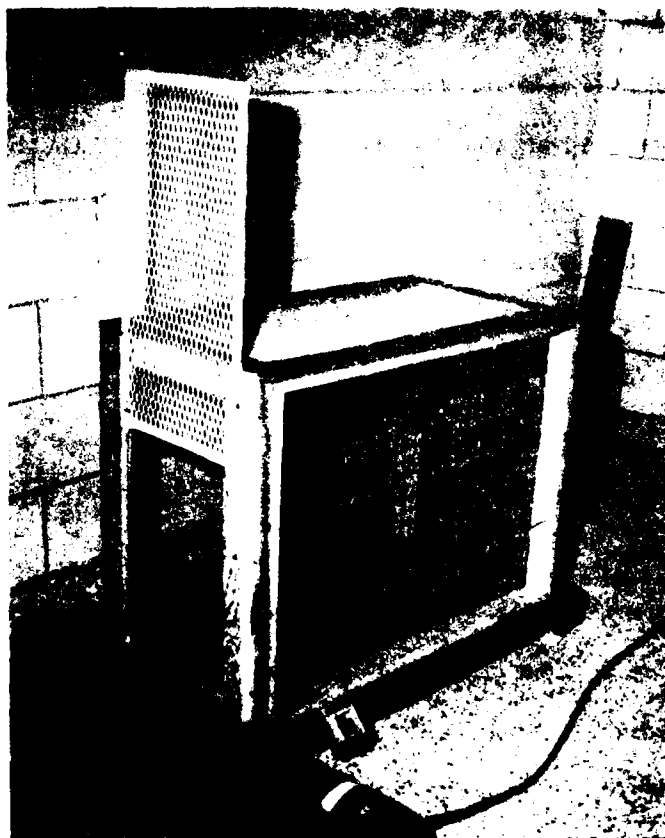track the motion of the leg. In addition, the design criterion of

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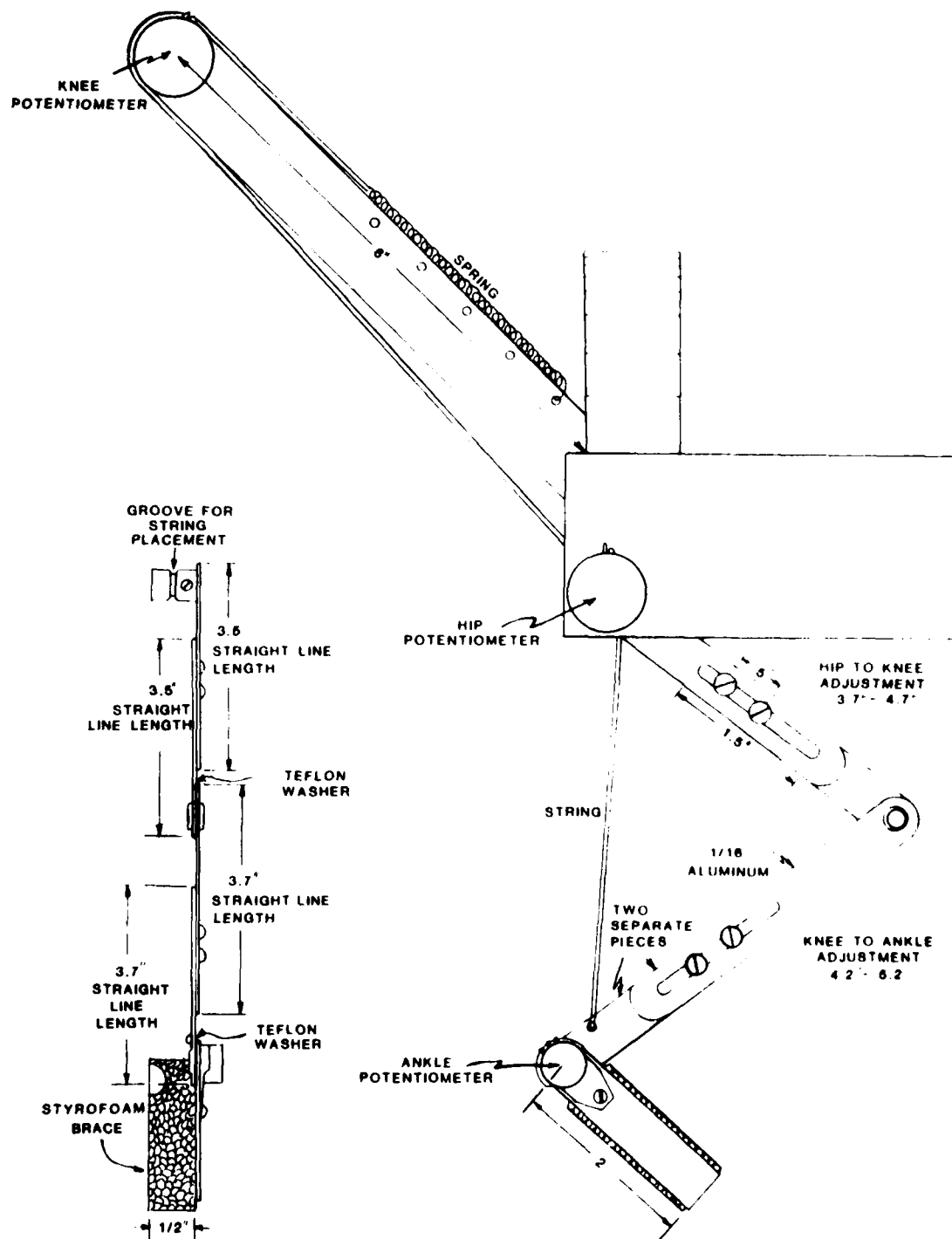Figure 22. Transparent Enclosure with Grid Network

Figure 23. Harness Leg Members and Measuring
Transducers

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limiting the lateral or side-to-side movement of each leg is achieved with this system.

Position information for each joint is provided by potentiometers. Three potentiometers (pots) are used for each leg harness providing rotation information from the hip, knee and ankle joints. The size and weight of the potentiometers was a major design problem. To minimize the weight transferred to the cat, only the ankle pot is attached directly to the leg harness. A small 50k$\Omega$ potentiometer attached at the ankle pivot measures the angle between the tibia member and the metatarsal member. Weighing only six grams, this device is well suited for placement on the leg harness. With this device included, the total weight of the leg harness is 40 grams. Both the hip and knee pots are attached to the support frame, and thus, no additional weight is applied to the leg harness.

With the weight constraint removed, 10-turn 20k$\Omega$ potentiometers were used for the hip and knee measurement devices (10-turn pots were used because of ease of rotation and availability). The shaft of the hip pot supported the leg harness system. With the body of the pot attached to the positioning arms and the shaft attached to the femur member, movement of the thigh is measured.

Angular change in the knee joint is translated to the knee potentiometer using a string and pully system. As can be seen in Figure 23, a spring supplies the required tension to keep the string taut. The travel of the string around the rubber pully on the shaft of the knee pot measures the change in the knee angle. The law of

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cosines defines this representation such that the knee angle can be expressed as:

$$\text{Knee} \; \measuredangle = \arccos[(F_\ell^2 + T_\ell^2 - S_\ell^2)/2F_\ell T_\ell)]$$

where; $F_\ell$ = length from knee pivot to hip pivot

$T_\ell$ = length from knee pivot to insertion of string in the tibia member

$S_\ell$ = length of the string measured from the hip pivot to its insertion in the tibia member.

This system for knee angle measurement provided an additional incidental improvement to this experiment. Because of the pulling force of the spring, the leg members impose a zero effective weight on the cat when in a standing stance. This system is, therefore, less restrictive than it would be if the full weight of the harness was transferred to the leg.

## Electronics

The principle by which the potentiometers supply the position information is that of measuring the rotation of a specified member. A voltage divider circuit is created when a constant voltage is supplied across the potentiometer and the output voltage is taken from the pot wiper lead. Rotation of the pot's shaft causes a change in the resistance ratio and will change the output voltage. In this manner, a voltage level is produced that is proportional to the rotation of the pot shaft. The signals produced by the potentiometers are sent to the circuit shown in Figure 24. Each potentiometer signal travels through
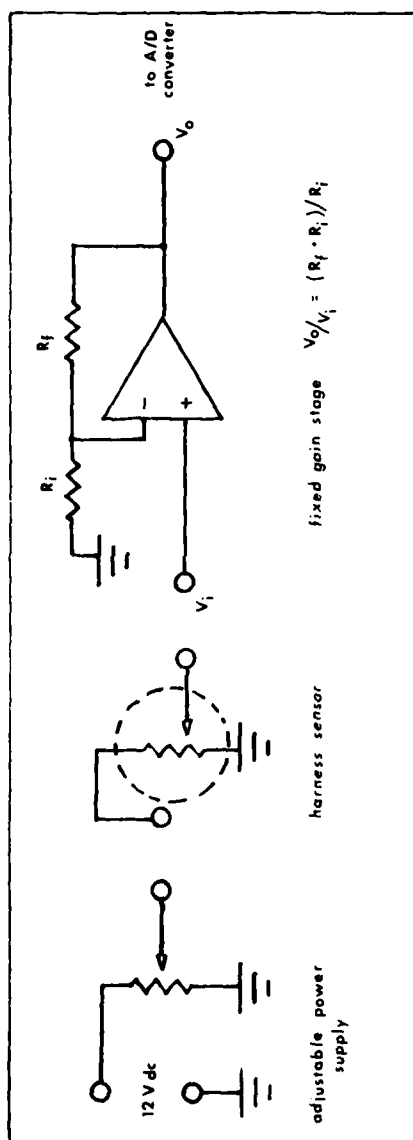
49

Figure 24. Schematic of Harness Circuit

its own circuit which provides two functions; 1) to allow for gain

adjustment and 2) create a low impedance output signal.

Analog to Digital (A/D) converters will digitize the position

signal produced by the potentiometers. To obtain maximum resolution

from the converters, the voltage range corresponding to the leg motion

must be identical to the input voltage range of the A/D. Trim potentio-

meters accomplish this adjustment by controlling the input voltage to

the position pots. Since the circuit shown in Figure 24 produces a

fixed gain for each signal, the input voltage is proportional to the

output voltage. By physically positioning the leg members to their

corresponding maximum travel, the output voltage can be adjusted to the

desired level. Each potentiometer has independent adjustment capa-

bilities. The individual parameters used in the complete harness circuit

are listed in Table III.

The low impedance characteristic of the amplified output signal

improves the accuracy of the A/D converters. Physically positioning

the harness members and measuring the angle of the members and the

corresponding output voltage from the potentiometers allowed the formu-

lation of voltage-angle relationship. Figures 25, 26 and 27 show the

voltage-angle relationship for the left leg harness. The data points

in the figure represent the actual measured values. A best-fit curve

was then traced to the data points. In each case, the curve produced

a relationship that can be considered linear for all practical purposes.

The small deviations from the linear relationship are caused by

imprecise characteristics of the current position potentiometers.

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## TABLE III

### Harness Circuit Compounds†

| Channel | Angle Measured | Harness potentiometer | Gain |
|---------|----------------|----------------------|------|
| 1 | right ankle | 1-turn 50 kΩ | 1.25 |
| 2 | right knee | 10-turn 20 kΩ | 1.25 |
| 3 | right hip | 10-turn 20 kΩ | 1.8 |
| 4 | left ankle | 1-turn 50 kΩ | 1.25 |
| 5 | left knee | 10-turn 20 kΩ | 1.25 |
| 6 | left hip | 10-turn 20 kΩ | 1.8 |

†The trim-pots used in the adjustable power supply were 10 kΩ.

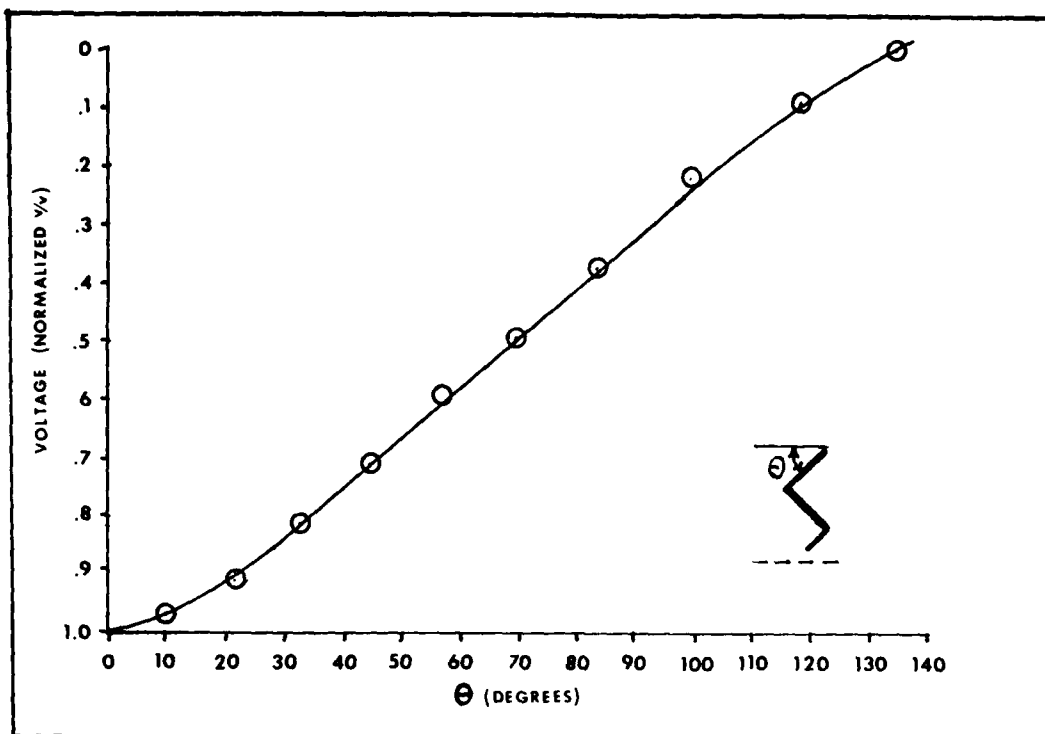LM1458 operational amplifiers were used in the gain stage.
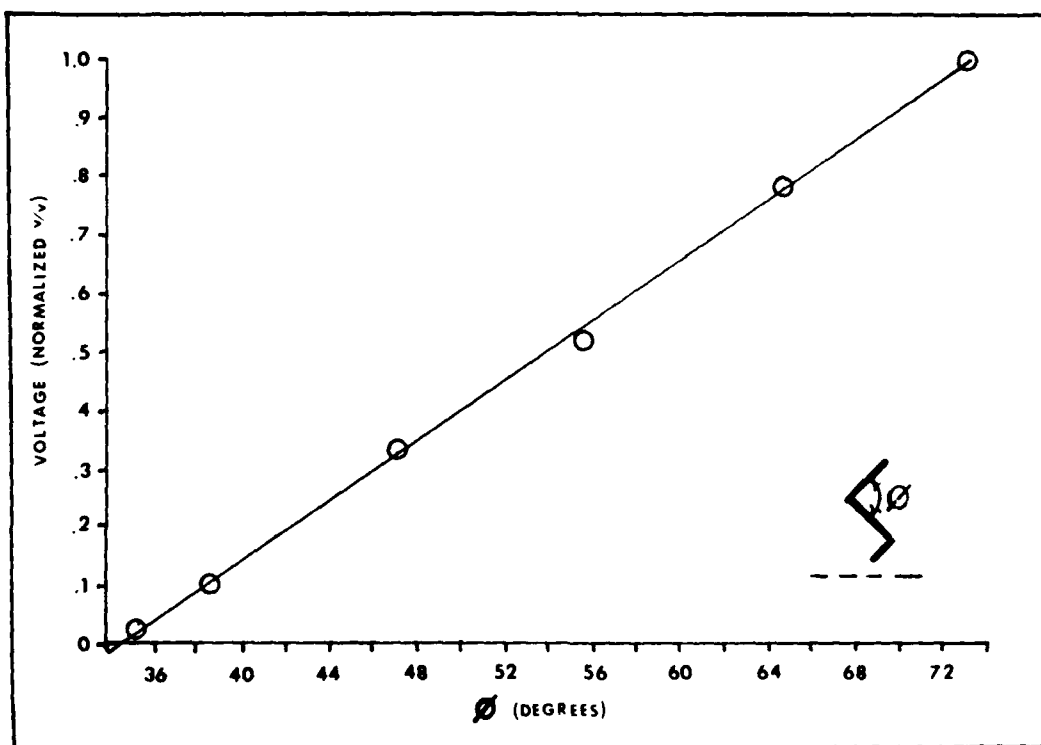
Figure 25. Voltage-Angle Relationship for
the Left Hip



Figure 26. Voltage-Angle Relationship for
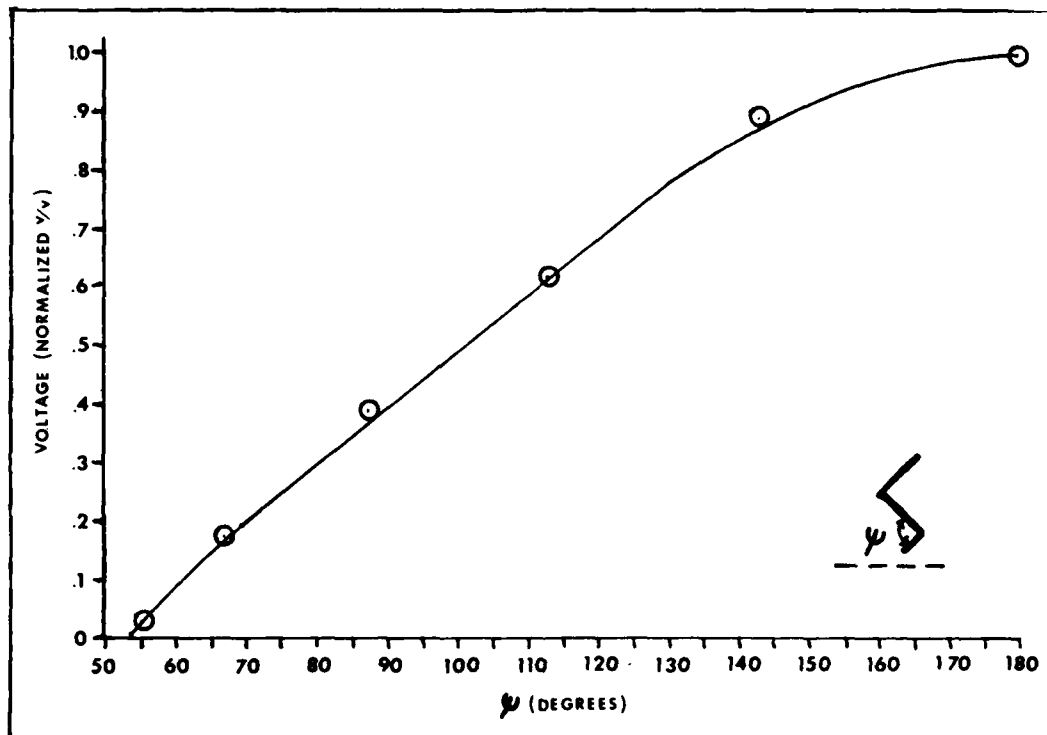the Left Knee

53

Figure 27. Voltage-Angle Relationship for
the Left Ankle

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Before actual interface with the A/D converters, high quality position pots will be substituted for the present units.

Sample output from the harness potentiometers is shown in Figure 28. For any instance in time, the position of each leg member can be calculated. As an example, the position of the leg members corresponding to the points A and B in Figure 28 are illustrated in Figure 29.

Calculating the angle relationship of leg members from the input voltage will eventually be accomplished through look-up tables in a computer. Binary numbers created by the A/D converters will correspond to specific angles of a joint. A simple precalibration routine will assign angle values to the binary numbers as follows. Minimum and maximum angles of each joint will be physically set and the corresponding output signals will be "locked on" by the computer. Using the linear relationship between the voltage output and angle, the routine will assign corresponding binary numbers to the intermediate angle values.
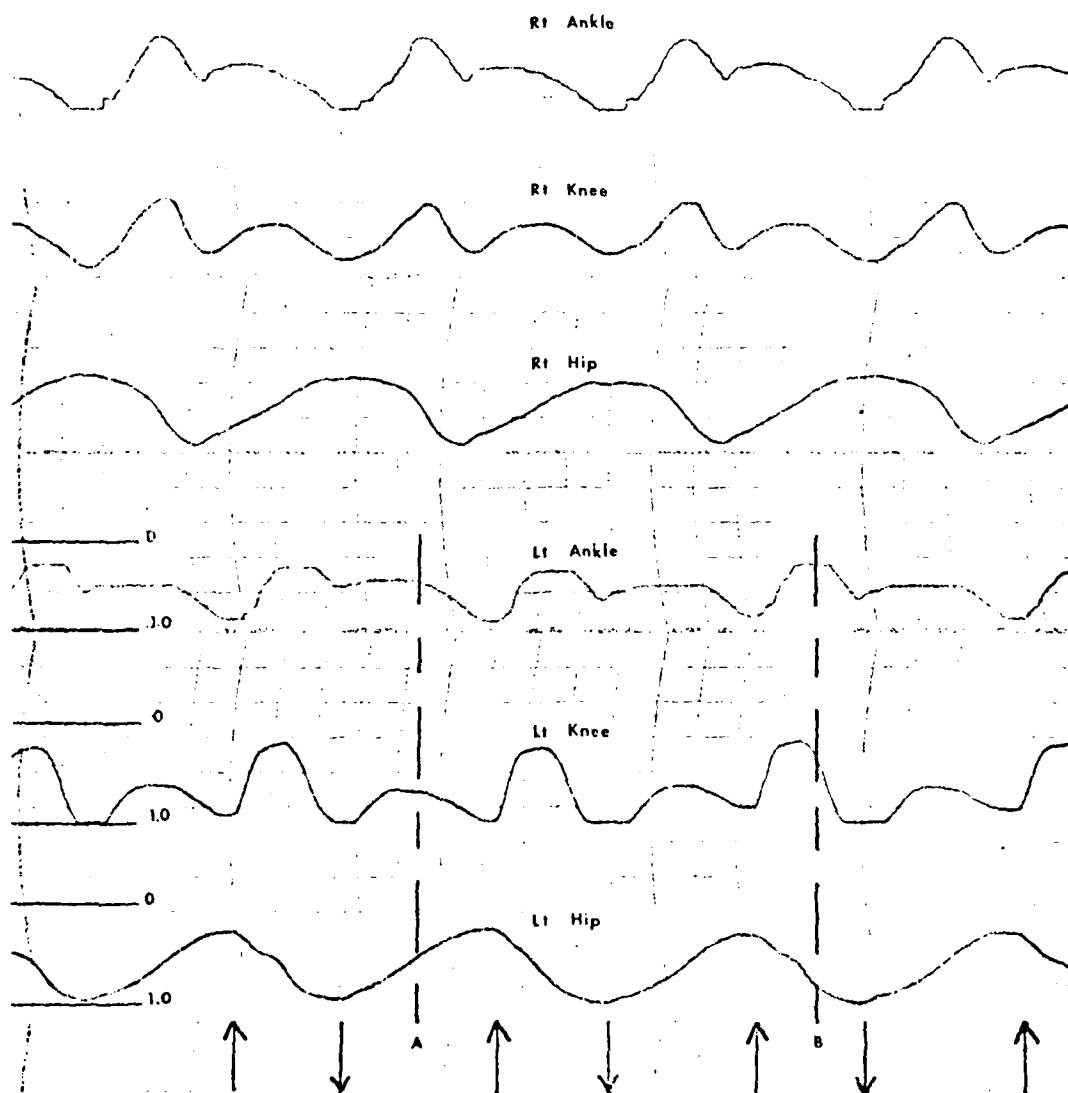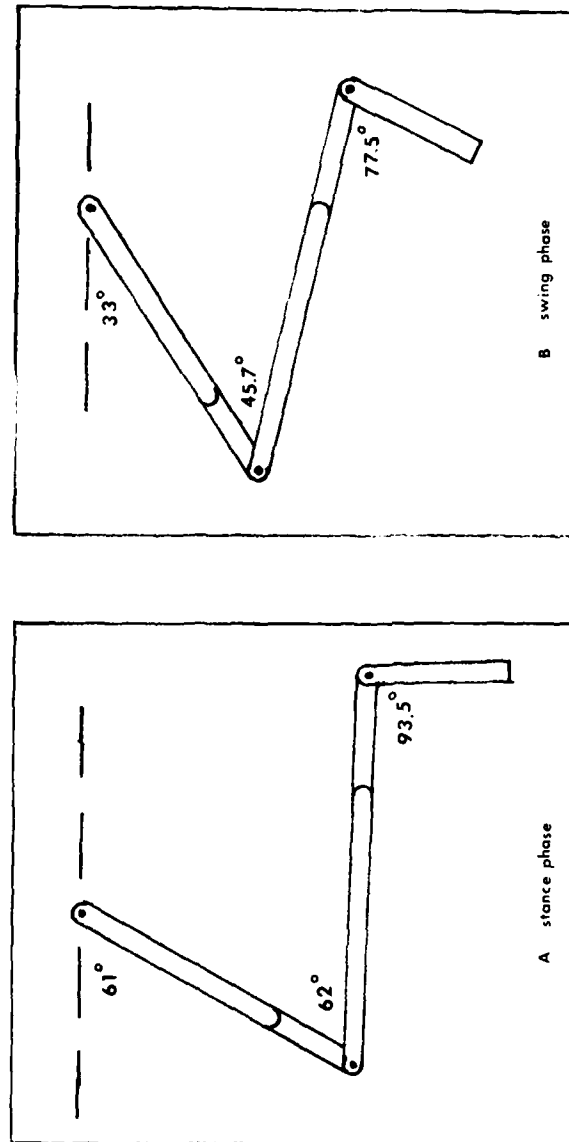
Figure 28. Sample Output From the Leg Harness

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Figure 29. Example of Leg Members Position

## VII. Experimental Procedures

Two adult cats weighing approximately 3.5 kg were selected for use in this project. Cat #156 was a male and cat #153 was a female. The cooperative nature of the animals was an essential part of this project. Not only did the cats have to voluntarily walk on a treadmill but do so while strapped in the harness assembly. Of the two cats chosen, only the male would copperate with the hardware. The electromyogram (EMG) data presented in this thesis was obtained from the male cat.

## Preparation of the cat

Isolation of individual muscle activity during the step cycle was achieved by inserting silver electrodes into the muscle body. Two electrodes were implanted in the muscle to generate the EMG signal. The ground reference was supplied by a surface electrode applied to the upper hip area. Each experiment recorded the activity of three muscles in one leg along with the position information produced by the harness. Figure 30 shows a close-up photograph of placement of electrodes in the left leg in which the biceps femoris, gastrocnemius and tibialis anterior are the muscles under consideration. With the harness attached as shown in Figure 31, the electrode leads are undisturbed and interface with the electrode board of the recorder.

Alternating the leg used for the EMG data was done so that destruction of the leg tissue was kept to a minimum.

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Figure 30. Placement of Electrodes for EMG Analysis



Figure 31. Harness and EMG Configuration

The electrodes inserted into the muscle are composed of a teflon coated silver wire (99.99% Ag). The silver wire has a 0.003 in outer diameter with a 0.0015 in coated layer of teflon providing the insulation. The wire is threaded through a 22ga 1 1/2in hypodermic needle. Using micro-tweezers, approximately 2mm of the teflon coating is stripped from the silver wire protruding from the needle tip. The bared silver is then bent into a hook which will lodge in the muscle when the needle is withdrawn. The opposite end of the wire is cut 5cm from the base of the needle and 2-3cm of teflon is stripped away in the same manner as before. The electrode and hypodermic needle is then sterilized using a gas sterilizer. Figure 32 shows the electrode and needle system prior to insertion.

Preparation of the cat involved complete shaving of both rear limbs, the lower back and pelvic area, forward to the middle of the rib cage. A 0.5cc intramuscular (IM) injection of ketamine is given prior to insertion of the electrodes. With the cat "knocked down", the leg to be used is scrubbed with a veterinary betadine solution.

Shortly after the ketamine is introduced, the hypodermic needle is inserted into the muscle under consideration. Two electrodes are inserted into the midsection of the muscle with the separation of the electrodes being approximately 3cm. The localization of the electrode was controlled before and after each session by electrical stimulation and palpation of the twitching muscle and its tendon. Additional verification of localization was accomplished during the experiment by comparison of the individual EMG signals to corresponding data presented by Engberg and Lundberg (1968).
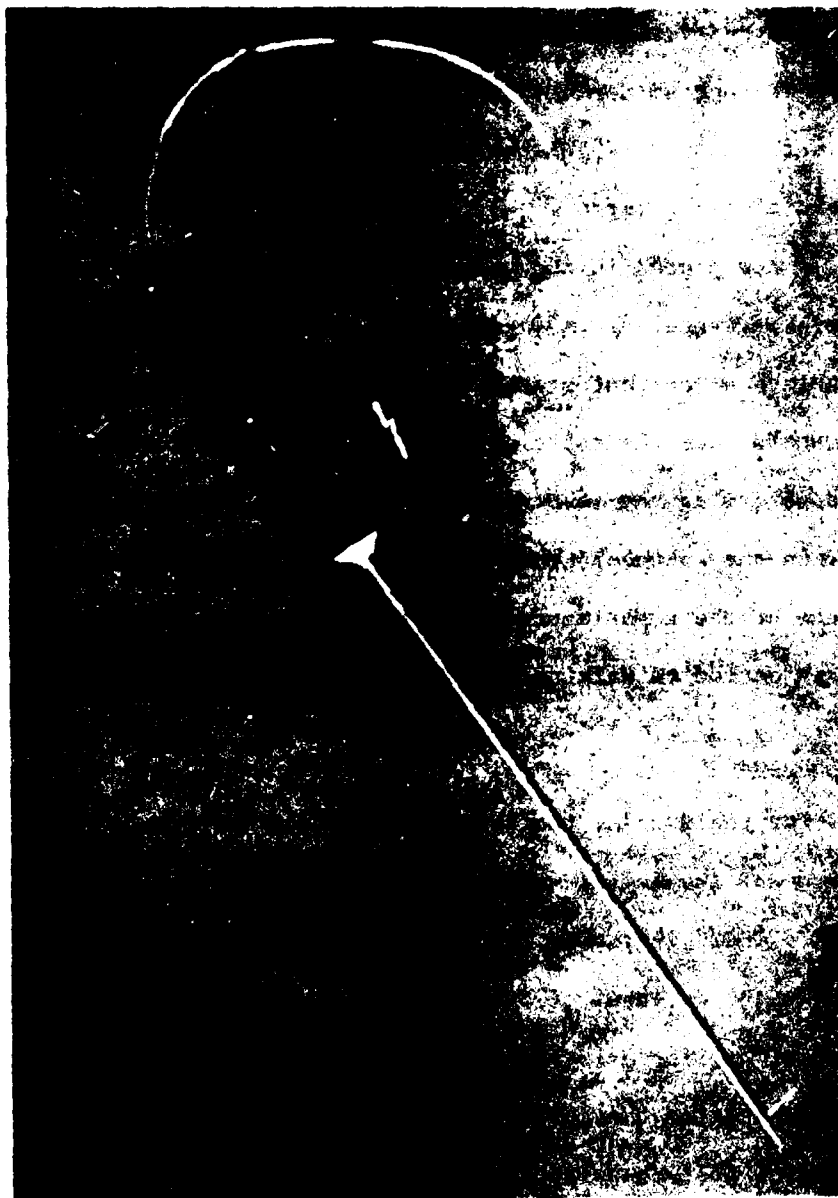
Figure 32. Electrode and Hypodermic Needle
Prior to Insertion

Special care is needed when securing the exposed electrode to the skin. Because of the slippage of the skin over the muscles, electrodes are easily dislodged if slack in the exposed wire is not provided. The exposed silver is then soldered (low-temperature) to a 60cm length of 32ga thermoplastic insulated hook-up wire which will interconnect to the electrode board of the recorder.

The cat is now placed in the harness assembly and the tail clamp and leg members are secured. A 30 to 60 minute period is necessary for the cat to achieve a coherent state. Determining the point when the ketamine did not affect the cat's performance was done by checking pupil dialation and observing the response of the cat when the treadmill was activated. When the cat could produce a smooth, constant gait, the recording stage of the experiment could begin. The time required from the ketamine injection to walking status averaged two hours.

Experimental Approach

Once the cat could walk, the treadmill was activated and the resulting motion of the leg along with the EMG signals were recorded by a Grass model 78 EEG/Polygraph. The six signals generated by the harness went directly in the J5 input of the Grass which produces a full scale pen deflection of 5cm for a 1 volt RMS input signal. The output of the potentiometers measuring the motion of the harness was adjusted so that the maximum travel of each potentiometer would produce a 1 volt signal. These signals produced by the harness comprise the first six channels of the Grass and represent the motion of the: (1) right ankle, (2) right knee, (3) right hip, (4) left ankle, (5) left knee, and (6) left hip.

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The three EMG signals produced during each experiment were coupled

to the electrode board supplied with the Grass model 78. Calibration

of the three channels recording the EMG was done prior to each experi-

ment. A representative sample of the data recorded is shown in Figure 33.

The characteristic spiking of the EMG was attenuated so that the initial

activity of the muscle could be distinguished more clearly. The inter-

face with the recorder along with recording control setting is discussed

in Appendix B.

With the full harness system incorporated, the treadmill belt speed

was varied to obtain data for different speeds of locomotion. Four

distinct treadmill speeds were used in each experiment; 0.09 m/s, 0.19 m/s,

0.25 m/s and 0.40 m/s. In each case, the speed of the treadmill never

reached the transition phase of trotting so that the cat maintained a

walking gait.

To analyze the restrictive nature of the harness assembly, the

above procedure was repeated for locomotion with the leg members removed

and locomotion with the only support to the animal was the front paws

and torso in the sling apparatus. Appendix B contains data recorded

from the three variations of harness control: A - full harness, B -

leg member removed but tail clamp still attached, and C - leg members

and tail clamp removed.† The treadmill speed used in all variations

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†The recording voltage range for the EMG signals was not correlated
to the physical characteristics (i.e., force, length) of the contracting
muscle. All that can be determined from the EMG data is the initial
activity of the muscle. However, comparative analysis can be done
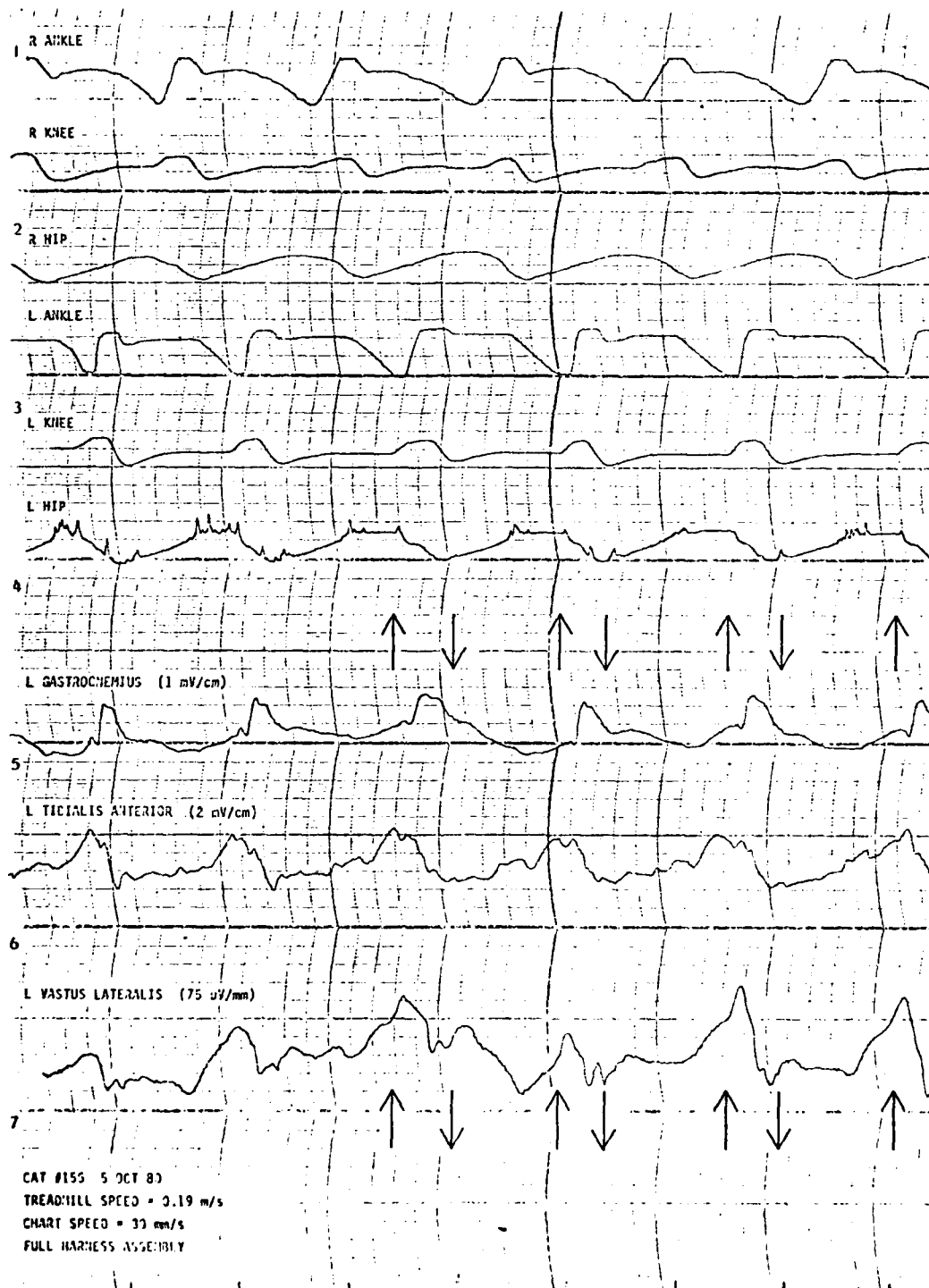between the three harness configurations.

Figure 33. EMG and Position Signals

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was 0.09 m/s. Because of this slow treadmill belt speed, the stance phase of the cat step cycle is about four times as long as the swing phase.

Configuration B produced a gait that was nearly identical to the gait developed in configuration A. The difference that could be seen while using configuration B was in small lateral movement of the limbs that was previously limited by the leg members in configuration A. In configuration C, the cat had to supply the posture control needed during locomotion. The cat was still in the sling assembly but the hindquarter area was not supported. The motion of the pelvis area had a small shifting (side-to-side) rhythm because of the phase difference in leg placement. However, there was no major change of the overall gait cycle when compared to A or B.

Comparing the individual EMG signals of configuration A, B and C, the basic activity of each muscle does not differ to any great extent. The peak-to-peak value for the gastrocnemius and tibialis anterior in configuration A is slightly greater than that value obtained with configurations B or C. In configuration A, the muscles of the shank must overcome the extra friction developed by the ankle pivot of the leg members which could explain the larger peak value. The distinct "spiking" of the tibialis anterior and biceps femoris in configuration C is mainly because of electrode slippage. Even with the increased activity, the basic EMG pattern of the tibialis anterior and biceps femoris developed in configuration C follows configuration A and B.

The variation of the vastus lateralis EMG between A and B is the more pronounced waveform in configuration B. Again, compensation for the harness can be seen. The spring-pully system of knee angle measurement aids in flexing the shank. The vastus lateralis must produce a slightly larger force to allow for the additional external force from the leg member system when in configuration A. Configuration C resembled that of A. The pulling force of the spring caused flexion of the shank (configuration A) and the weight of the hip area (configuration C), again causing flexion of the shank, explains the similarity of the vastus lateralis EMG of configurations A and C.

The semimembranosus activity varies little between the three configurations. The larger EMG amplitude produced in configuration C of the semimembranosus is due to the weight of the hindquarters. Since the semimembranosus is an extensor of the thigh, its rate of contraction greatly influences posture control.

EMG data recorded from the biceps femoris is extremely consistent between configurations A and B. In configuration C, the biceps femoris EMG shows bursts of activity that correspond to the peaks of the EMG developed in configurations A and B. As stated earlier, the additional noise is attributed to slippage of electrodes. The majority of the activity of the biceps femoris is during the swing phase which is very short when compared to the stance phase. To compensate for the additional weight of the pelvis area (configuration C) the biceps femoris must produce a larger force than needed when in configurations A and B.

## VIII.  Conclusion and Recommendations

Six muscles in the cat's rear leg that theoretically supply the
contractile force needed to control basic locomotion were isolated.
These muscles are:  gastrocnemius and tibialis anterior (extensor and
flexor of the metatarsus); vastus lateralis and biceps femoris (extensor
and flexor of the shank); semimembranosus and iliopsoas (extensor and
flexor of the thigh).  In the full harness configuration, the three
joints of the leg (i.e., hip, knee and ankle) are restricted to a single
degree of freedom.  That is, each joint can bend in only one plane.  The
individual muscles chosen provide the agonist and antagonist muscles for
each joint.  For the restrictive environment imposed by the harness
assmebly, the six muscles will control a two-dimensional movement of the
leg.

Since the data presented in this report were recorded from a
healthy cat, the movement of the leg while in the harness assembly was
influenced by the total array of muscles normally used during locomotion.
Whether or not the six isolated muscles can produce an adequate gait
cycle when the leg members are removed is an unanswered question at this
time.  Even with the knowledge that the six muscles chosen are either a
flexor or extensor, their contractions will cause some degree of lateral
and rotational movement of the leg.

When the cat is in the full harness configuration the need for
posture control is eliminated.  The tail clamp and sling assembly pro-
vide the support for the cat's pelvis area.  This is an ideal situation

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for initial attempts to induce functional motion of the leg by the computer controlled stimulators.

In each of the three harness configurations (i.e., A - full harness, B - leg members removed with tail clamp attached, C - leg members and tail clamp removed), the individual gait patterns produced by the cat during locomotion were nearly identical. However, when the tail clamp is removed, a marked difference in the EMG activity of the muscles is observed (see Appendix B). This increase in EMG amplitude and activity can be attributed to the need for active posture control during locomotion as compared to passive posture control developed during locomotion when pelvic support is provided by the tail clamp. The ability of the simplified six muscle system to provide active posture control during locomotion is dependent on the force characteristics of each muscle. Follow-on work will need to find the maximum contraction strength of each of the six muscles through tetanization. Using various modeling techniques, the forces needed for active posture control during locomotion can be determined. Comparison of the needed force to the available contractile force of the muscle under consideration will dictate whether additional muscles must be incorporated before the tail clamp can be eliminated. The force analysis work is currently being undertaken by a graduate student at the Air Force Institute of Technology (AFIT).

The eventual system that will control locomotion of a cat is shown in Figure 34. With the harness supplying the position feedback signals and the controlling muscles defined for the stimulators, the

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controlling software can be developed. The computer, stimulators and
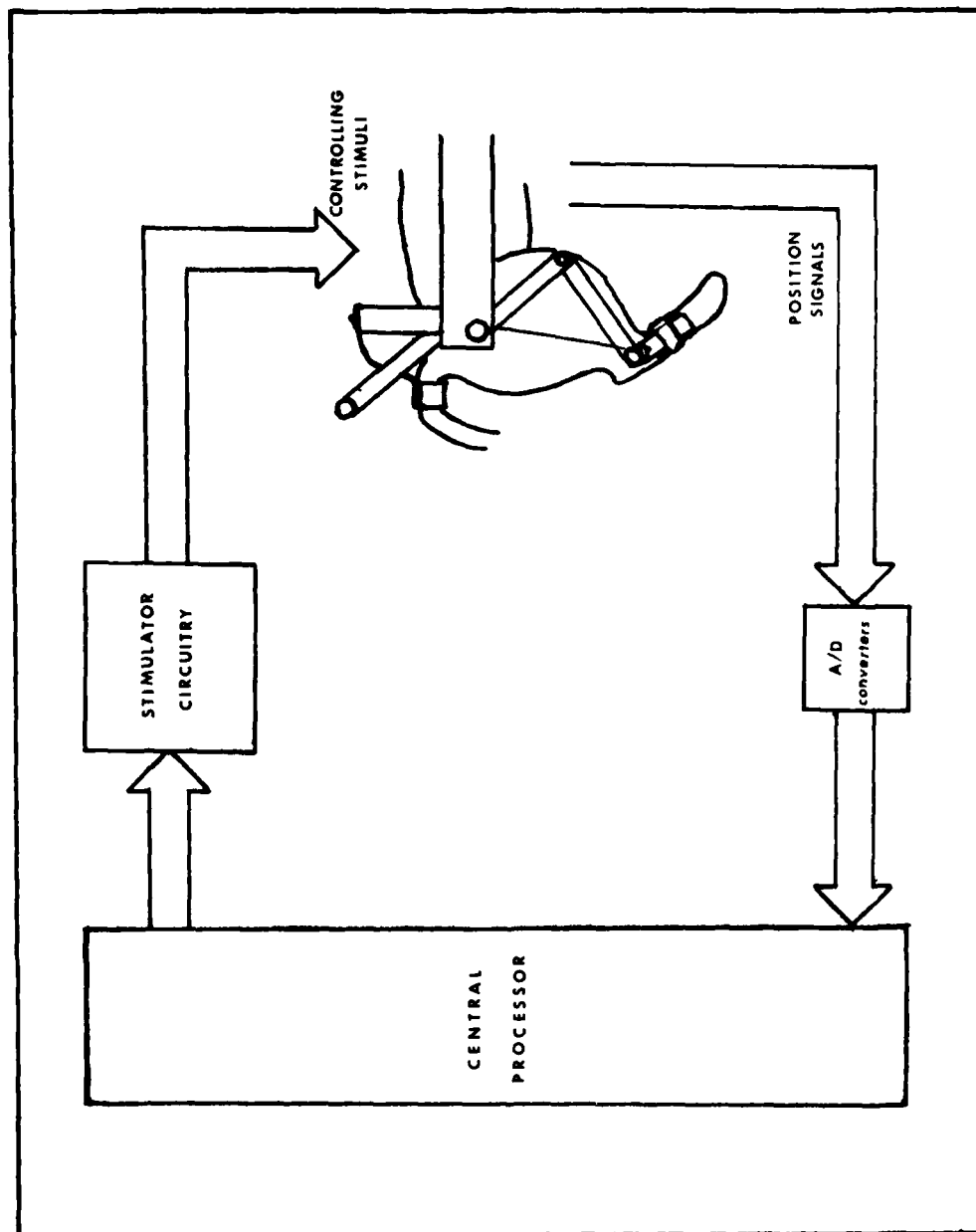assorted hardware used in this system are currently being built and
integrated.

Figure 34. System Diagram

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## Appendix A

The data shown in this section is used to illustrate the initial activity of the essential muscles during the gait cycle. Tables IV and V list the statistical average of the step cycle phases and initial point of muscle activity during locomotion at 0.19 m/s and 0.09 m/s respectively. Figures 35 (treadmill speed = 0.09 m/s) and 36 (treadmill speed = 0.19 m/s) illustrate the tabulated values as the leg progresses through the step cycle.

## TABLE IV

### Initial Activity During Step Cycle (0.19 m/s)

| Muscle | $\overline{X}$ (sec) | $\sigma(n-1)$[†] |
|---|---|---|
| Gastrocnemius | 0.11 | 0.010 |
| Tibialis Anterior | 1.20 | 0.066 |
| Vastus Lateralis | 0.28 | 0.063 |
| Semimembranosus | 0.15 | 0.021 |
| Biceps Femoris | 1.02 | 0.082 |
| Swing Phase | 0.46 | 0.046 |
| Stance Phase | 0.97 | 0.069 |
| Step Cycle | 1.43 | 0.075 |

$$^{†}\sigma(n-1) = \sqrt{\frac{\Sigma(X_i-\overline{X})^2}{n-1}}; \quad n = 15$$

TABLE V

Initial Activity During Step Cycle (0.09 m/s)

| Muscle | $\bar{X}$ (sec) | $\sigma(n-1)$[†] |
|---|---|---|
| Gastrocnemius | 0.11 | 0.015 |
| Tibialis Anterior | 1.88 | 0.121 |
| Vastus Lateralis | 0.27 | 0.025 |
| Semimembranosus | 0.14 | 0.039 |
| Biceps Femoris | 1.48 | 0.191 |
| Swing Phase | 0.54 | 0.042 |
| Stance Phase | 1.43 | 0.096 |
| Step Cycle | 1.97 | 0.091 |

[†]$\sigma(n-1) = \sqrt{\dfrac{\Sigma(X_i - \bar{X})^2}{n-1}}$; n = 10
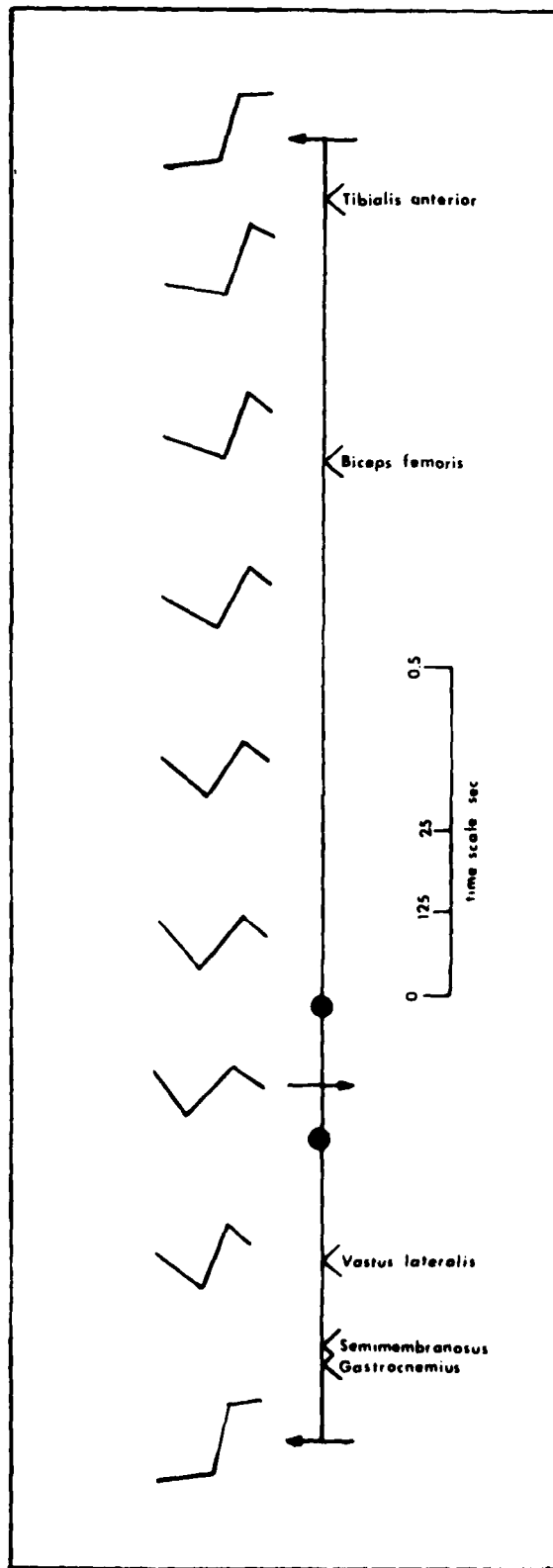
Figure 35. EMG vs. Step Cycle ( 0.09 m/s )

Figure 36. EMG vs. Step Cycle ( 0.19 m/s )

Tibialis anterior

Biceps femoris

Vastus lateralis

Semimembranosus

Gastrocnemius

0.5

.25

.125

0

time scale sec.

77
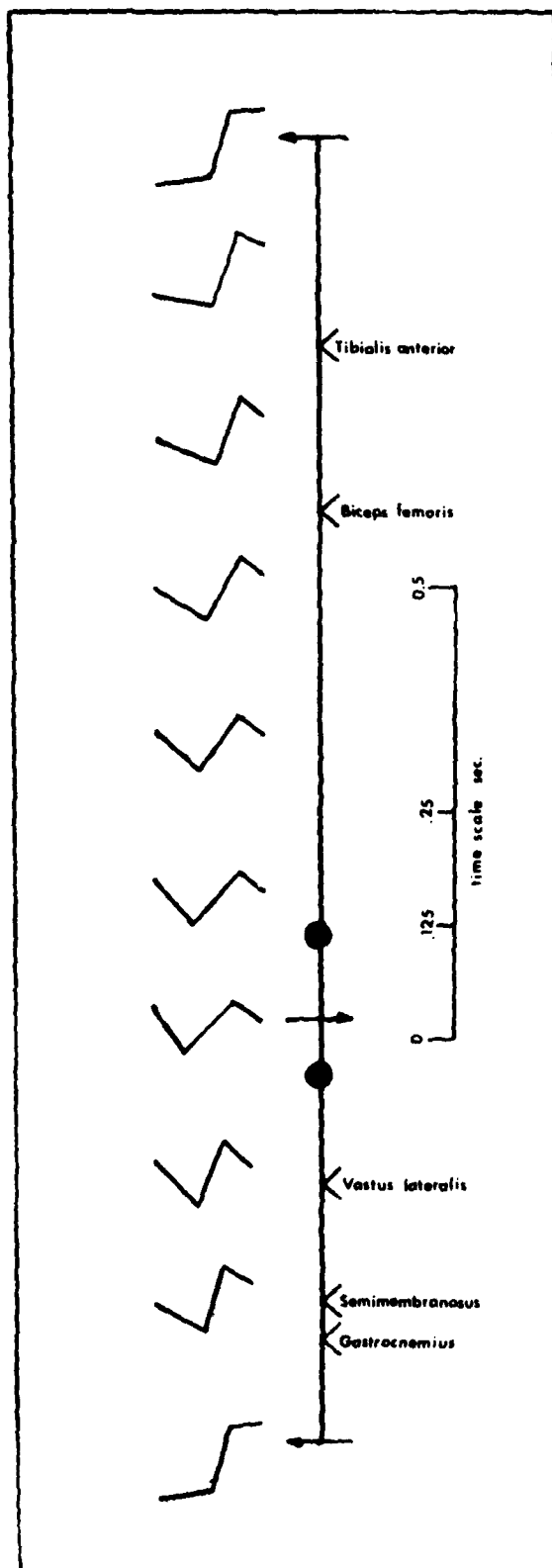
## Appendix B

This section contains additional experimental data. With the cat in the full harness configuration (A), EMG data from the essential muscles is shown for the four different treadmill belt speeds (i.e., 0.09 m/s, 0.19 m/s, 0.25 m/s and 0.40 m/s). EMG data developed in the two other harness configurations (i.e., leg members removed but tail clamp attached (B), and both leg members and tail clamp removed (C)) is shown for the treadmill belt speed of 0.09 m/s.

The EMG signal from each muscle went through a filter exhibiting the characteristics shown in Figure 37. The maximum frequency of the recording pens, set at 30 Hz, produced a smooth, distinct waveform. This uncluttered waveform showed initial low frequency activity of the muscle. High frequency EMG signals produced during strong muscular contraction are attenuated by the low pass filter (LPF). This can be seen in the attenuated EMG waveform of the gastrocnemius during the stance phase of the step cycle when the majority of contractile force is produced.

The integrated appearance of the EMG waveforms is attributed to the LPF characteristics. With a fall time constant of 250 ms, the LPF behaves as a crude integrator. The integration performed by the LPF explains the absence of characteristic "spiking" of EMG signals.
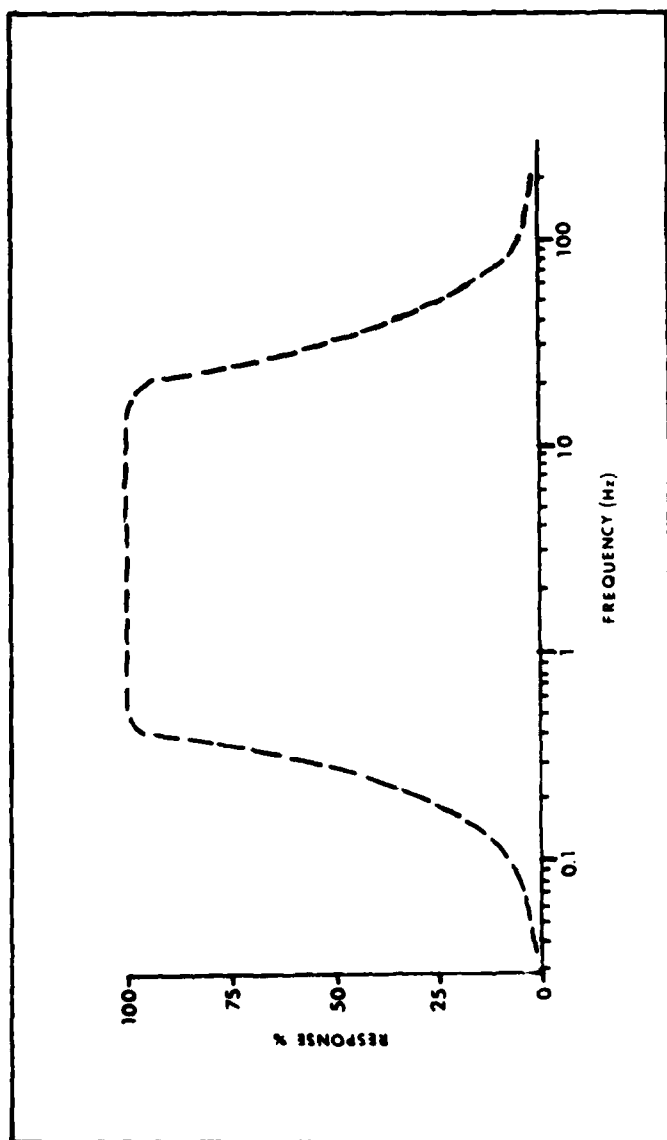
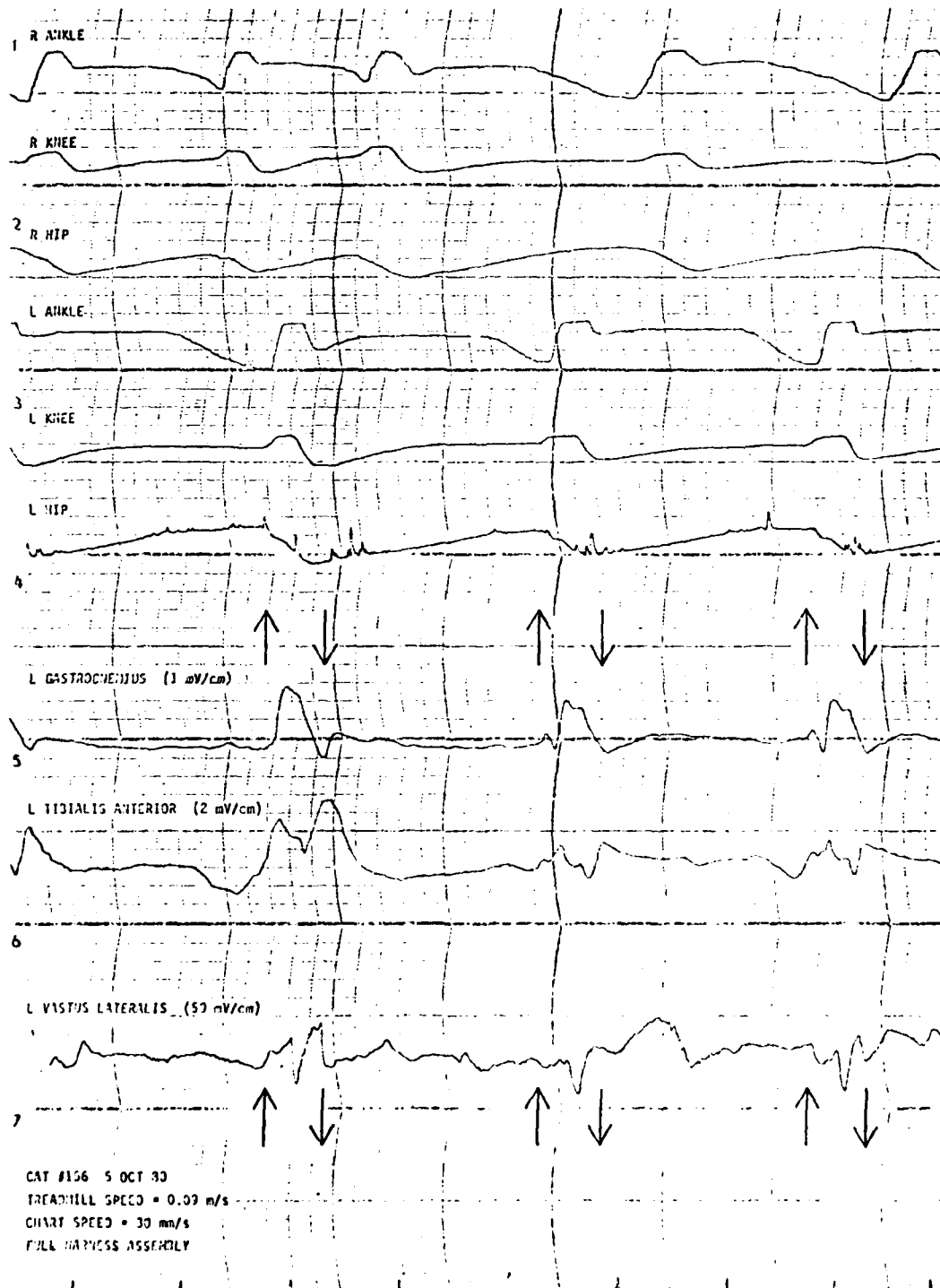Figure 37. Frequency Band Pass of EEG Recorder

R ANKLE

R KNEE

2 R HIP

L ANKLE

3 L KNEE

L HIP

4

L GASTROCNEMIUS (1 mV/cm)

5

L TIBIALIS ANTERIOR (2 mV/cm)

6

L VASTUS LATERALIS (50 mV/cm)

7

CAT #156  5 OCT 80
TREADMILL SPEED = 0.09 m/s
CHART SPEED = 30 mm/s
FULL HARNESS ASSEMBLY

Figure 38.  Experimental Data : Configuration A (0.09m/s)

Figure 38b

L ANKLE

3 L KNEE

L HIP

4

L SEMIMEMBRANOSUS (75 uV/mm)

6

L BICEPS FEMORIS (50 uV/mm)

7

CAT #156   7 OCT 80
TREADMILL SPEED = 0.09 m/s
CHART SPEED = 33 mm/s
FULL HARNESS ASSEMBLY

81
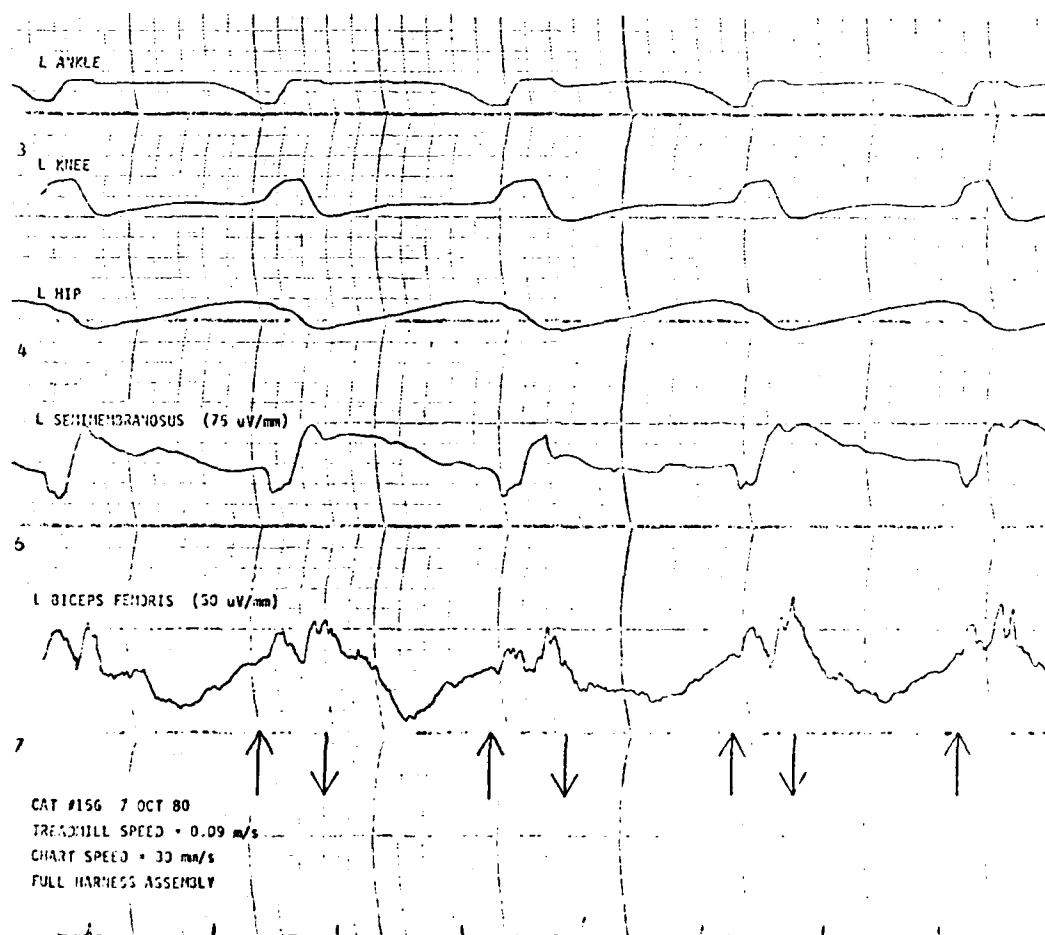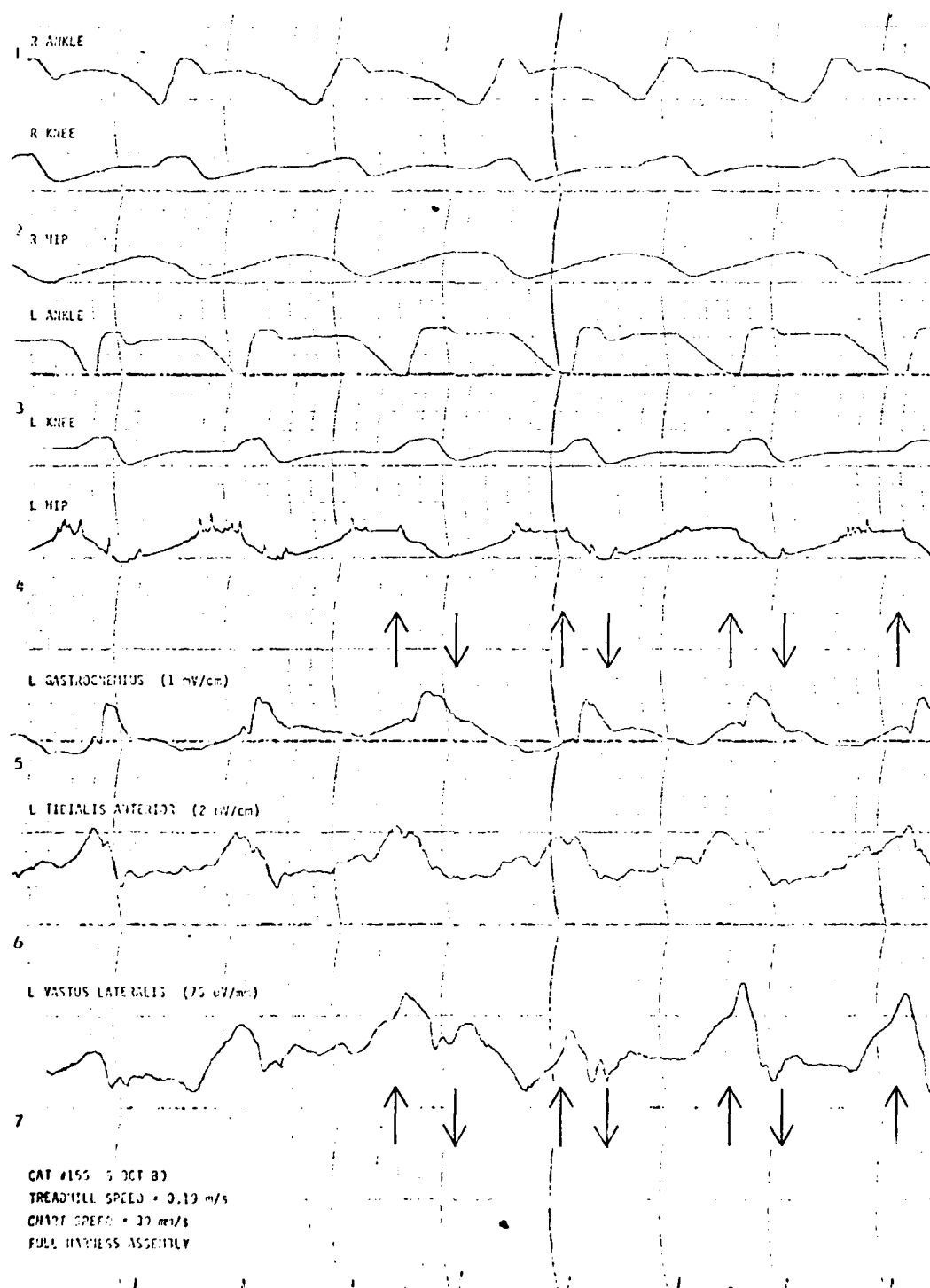
Figure 39. Experimental Data : Configuration A (0.19m/s)

L ANKLE

L KNEE

L HIP

L SEMIMEMBRANOSUS (75 μV/mm)

L BICEPS FEMORIS (75 μV/mm)

CAT #156  7 OCT 80
TREADMILL SPEED = 0.19 m/s
CHART SPEED = 30 mm/s
FULL HARNESS ASSEMBLY
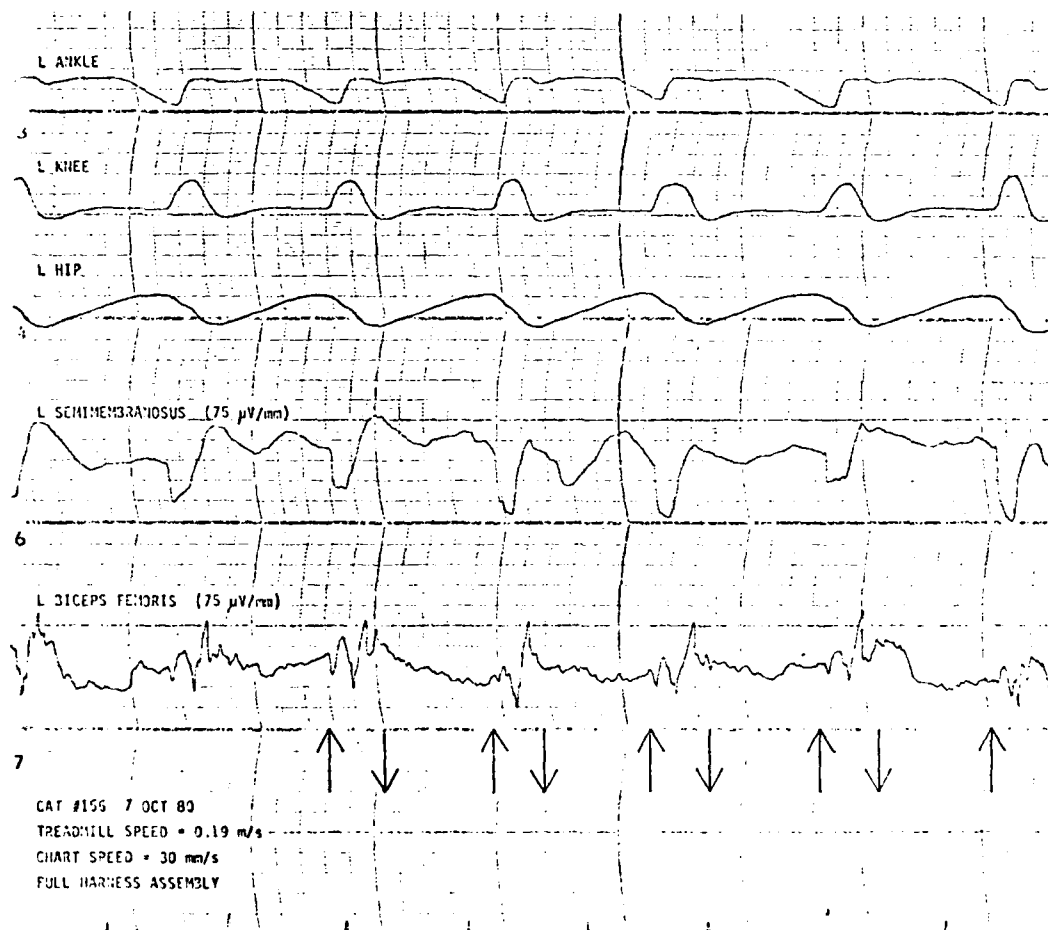
Figure 39b
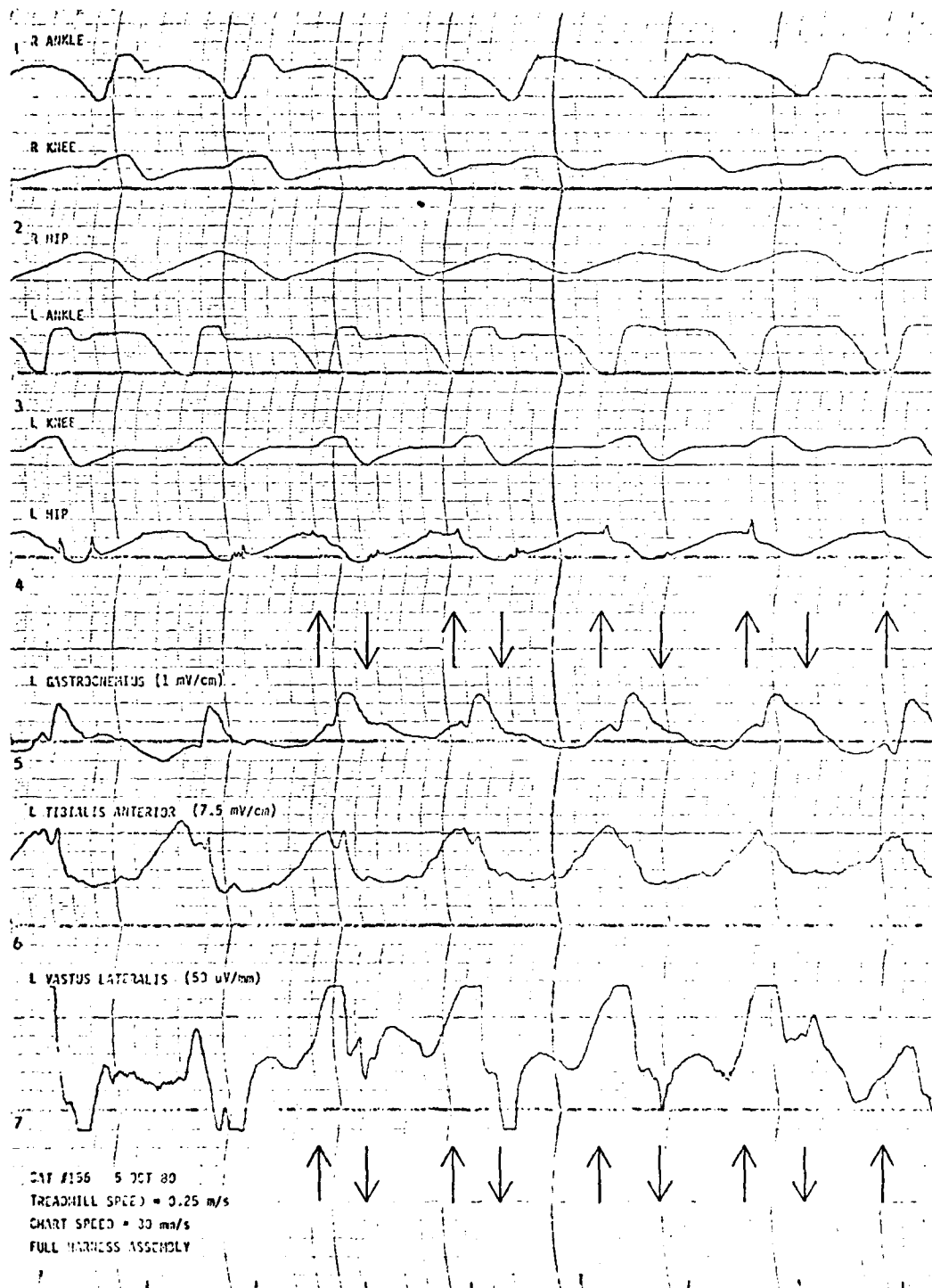
Figure 40. Experimental Data : Configuration A (0.25m/s)
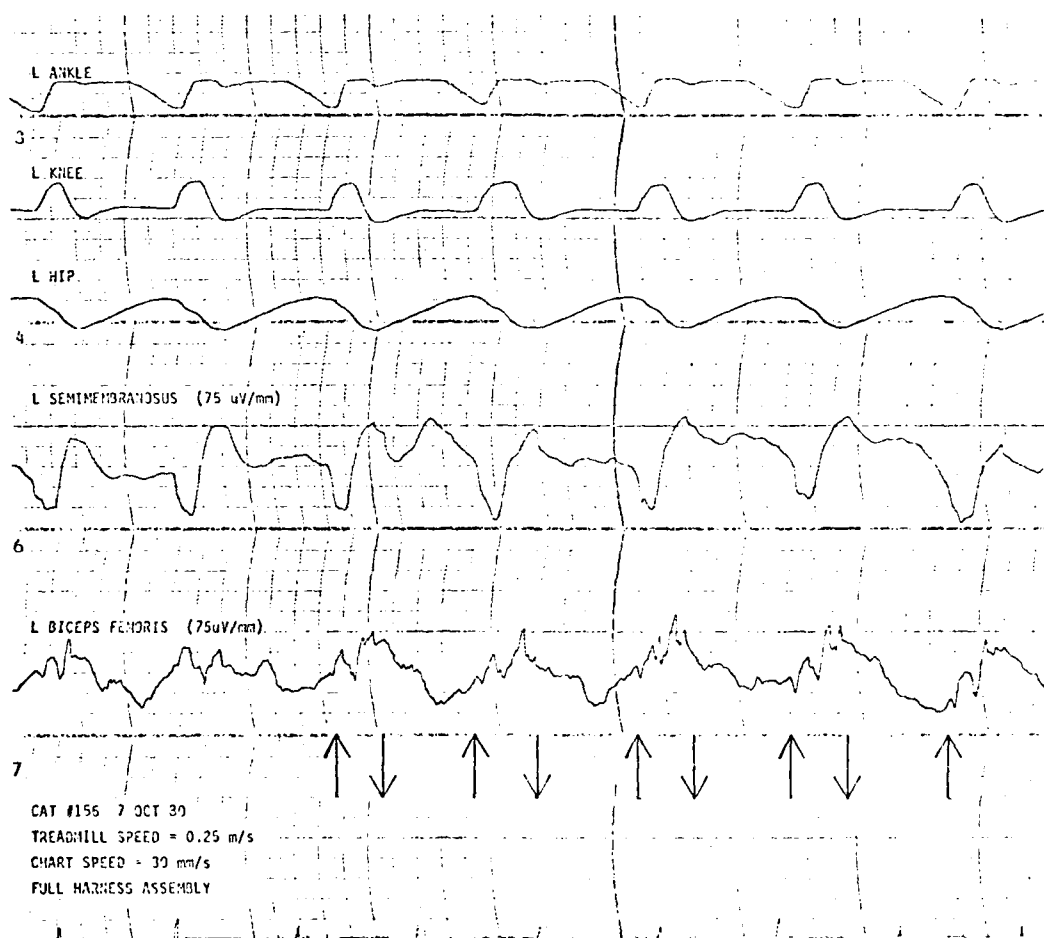
Figure 40b

1.0

2.8    2.5
3.2    2.2
3.6
4.0    2.0

1.1

1.8

1.25    1.4    1.6
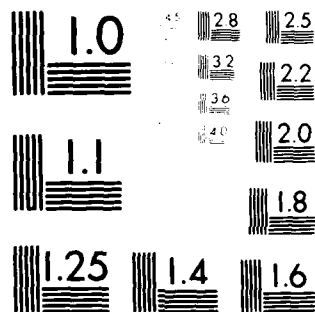
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A
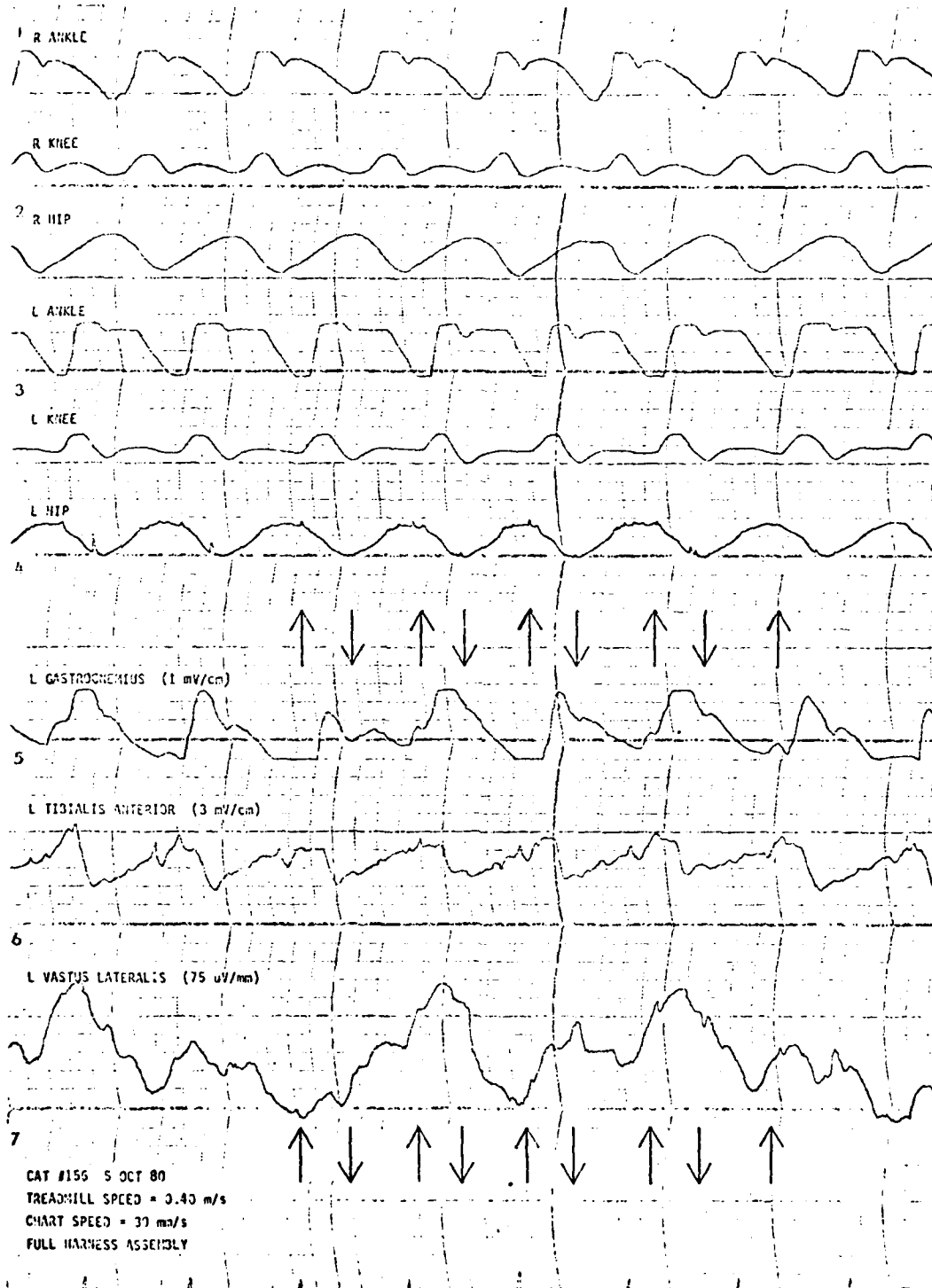
Figure 41. Experimental Data : Configuration A (0.40m/s)
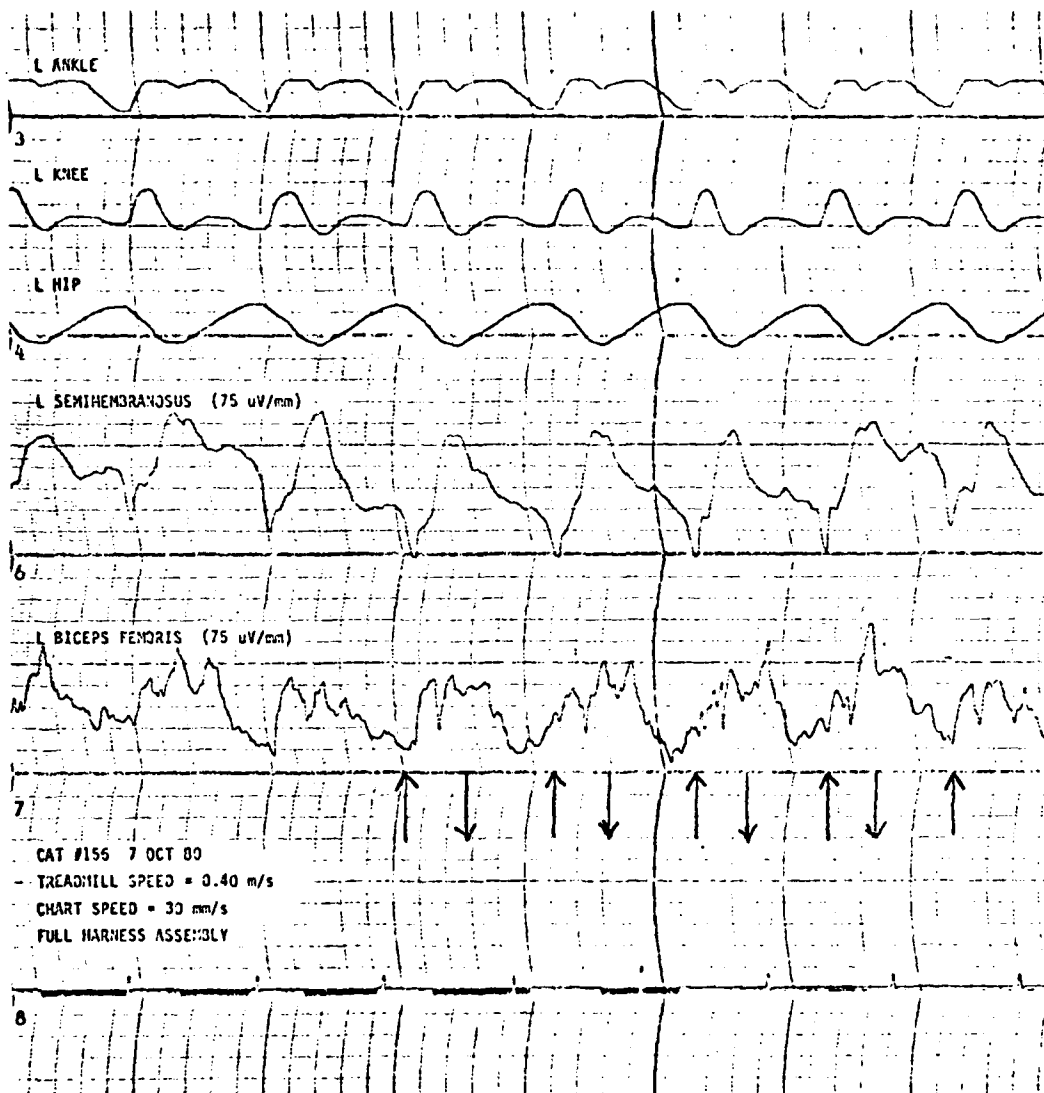
Figure 41b
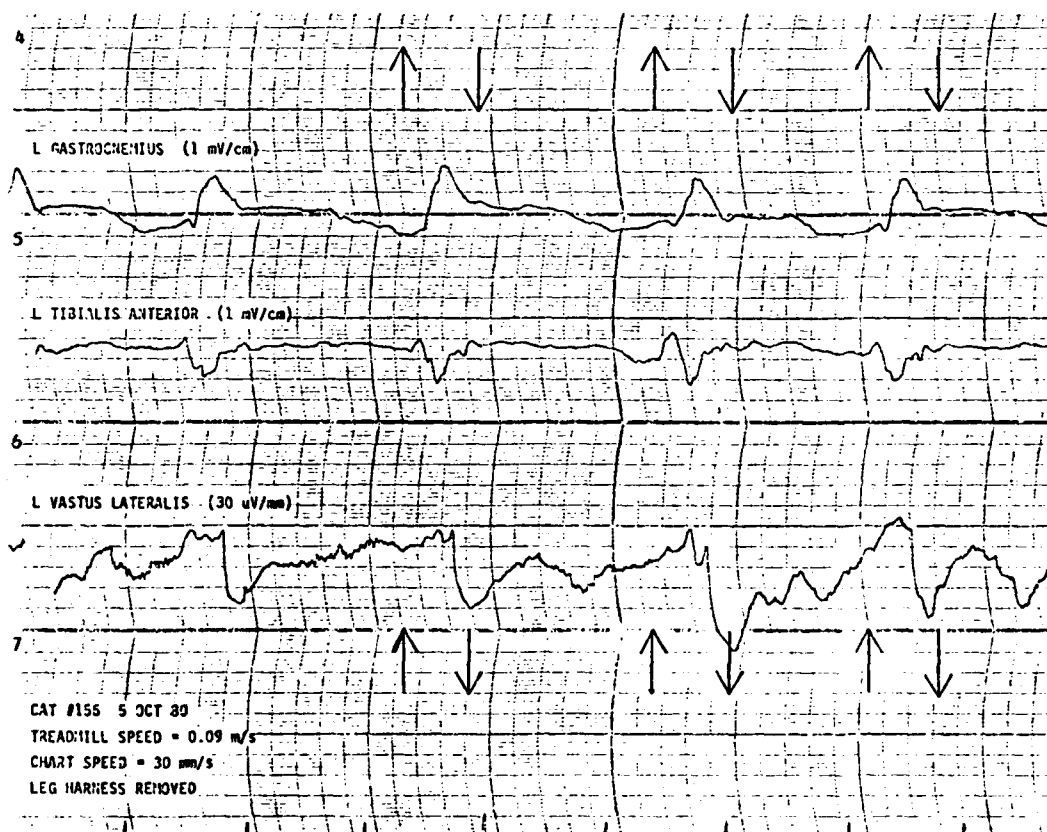
Figure 42.   Experimental Data : Configuration B (0.09m/s)
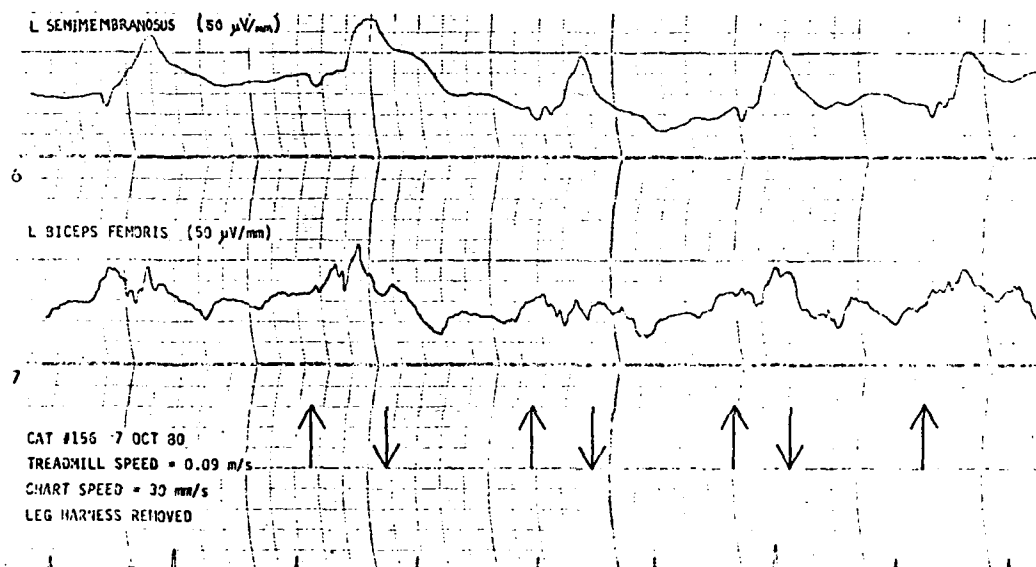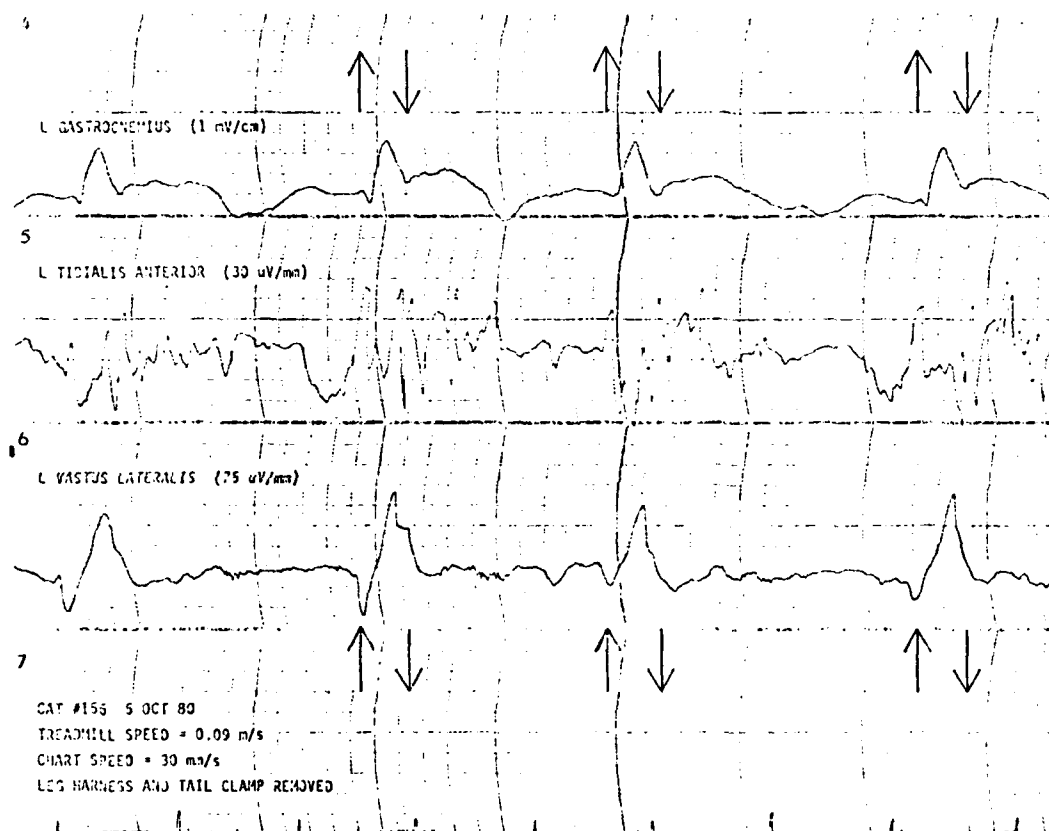
Figure 42b

89

Figure 43. Experimental Data : Configuration C (0.09m/s)

Figure 43b

91
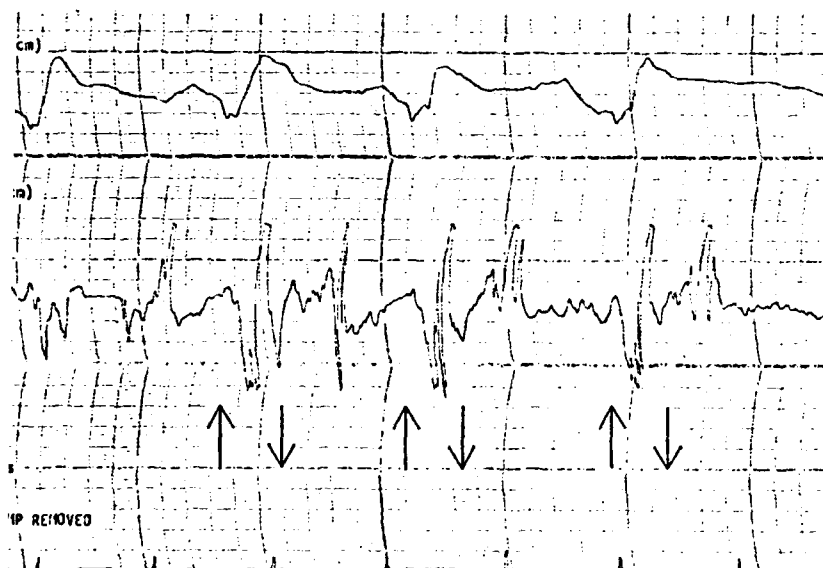
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8